Case 2:
The Isolated Synthetic Jet in Crossflow

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CFD Validation of Synthetic Jets and Turbulent Separation Control
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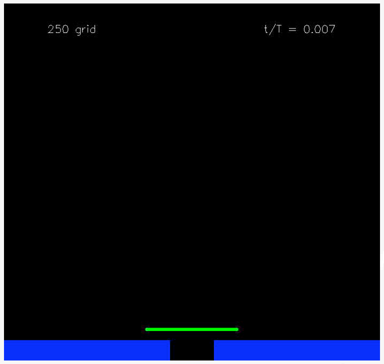
Overview of Presentation

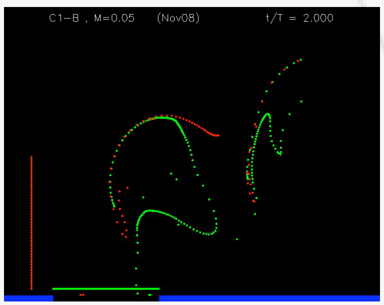
- Overview of Case 2
- Measurement Systems Utilized in Case 2
- Specification of the Boundary Conditions
- Measurement Systems by Location
- LDV Phase-Averaged Data
- 2D-PIV Phase-Averaged Data
- Stereo PIV Phase-Averaged Data
- Summary

Langley Research Center Workshop on the CFD Validation of Synthetic Jets and Turbulent Separation Control

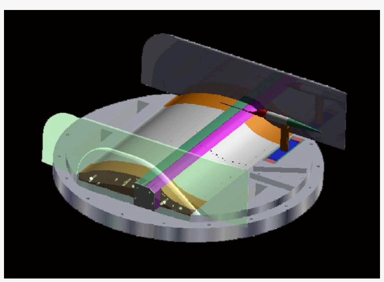
COMPLEXITY



Case 1: The Isolated Synthetic Jet

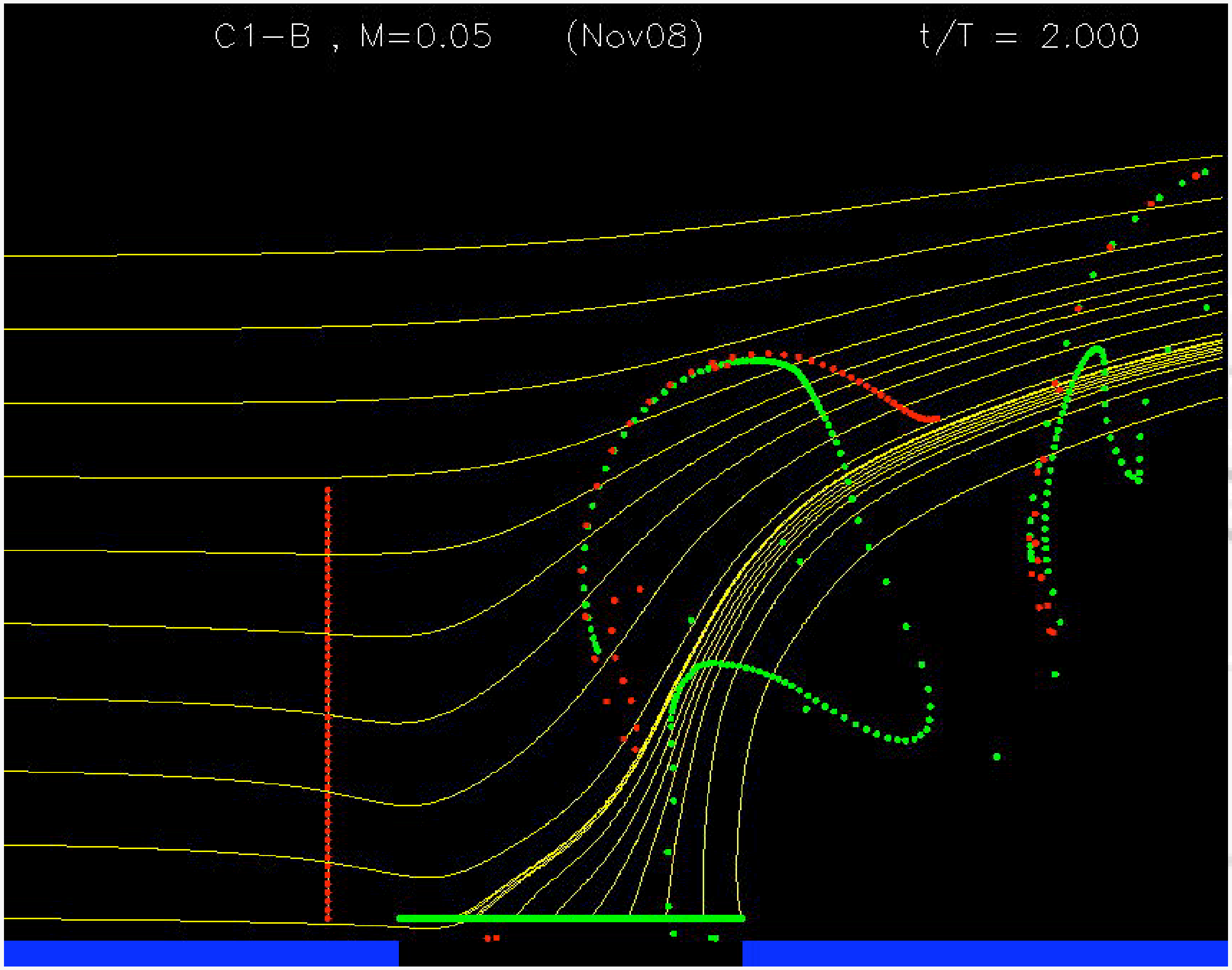


Case 2: The Isolated Synthetic Jet in a Crossflow.



Case 3: Turbulent Separation Control of the Flow over a Wall Mounted hump.

How did we arrive at Case 2?



- Schaeffler (2003)
  - Different orifice geometries
  - Application of PIV

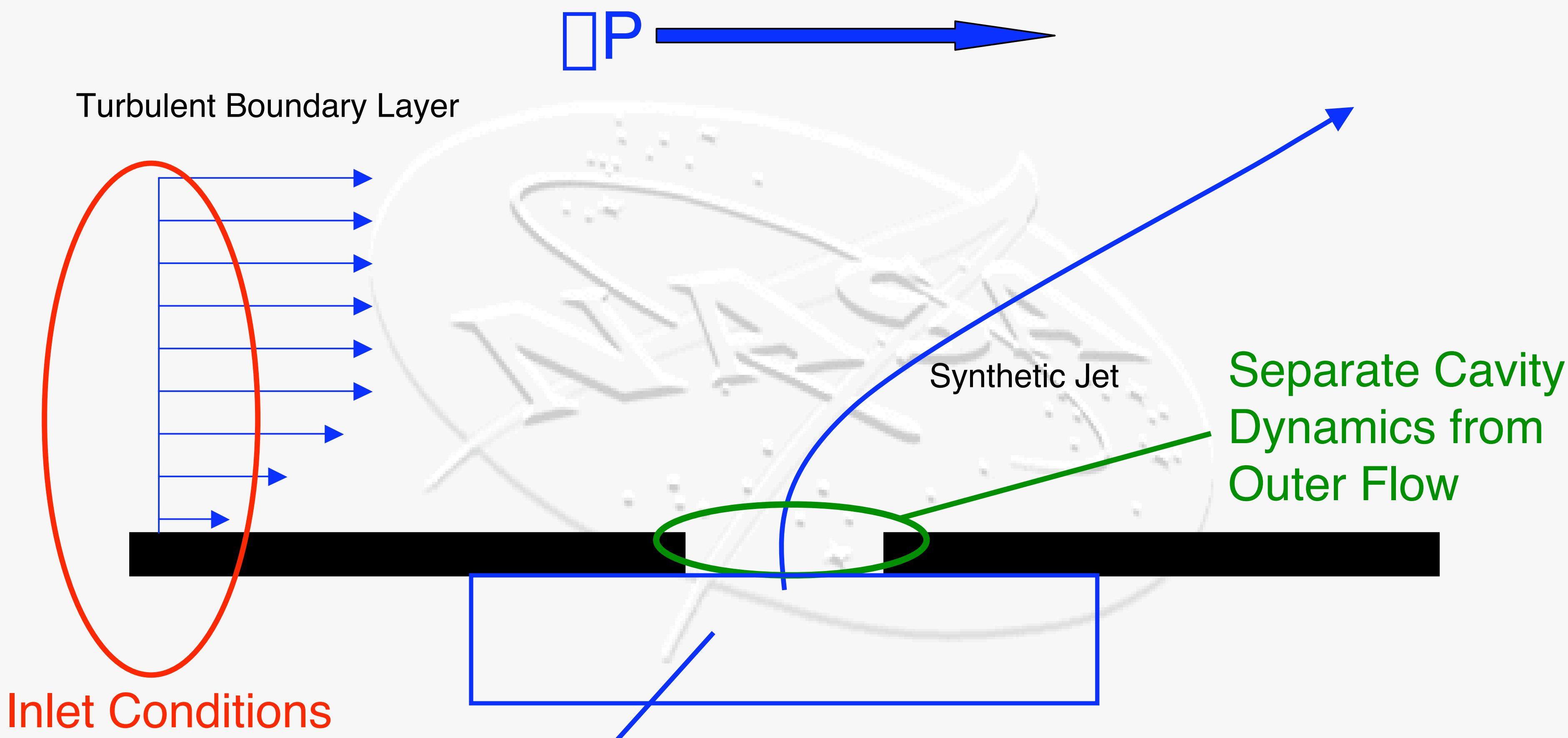
Benchmark Candidate?
  - Mach number to low
  - Lack of Cavity parameters
  - Orifice too small

- Smith (2002)
  - Hot wire - Total Velocity
  - Mean Flow Only
  - No Cavity Parameters

- Zaman and Milanovic (2003)
  - Cross Wire (2 components)
  - No Cavity Parameters
  - "blows through" BL

Each of these experiments was designed to "build a better actuator", not to build a "better computation".

Overview of Case 2

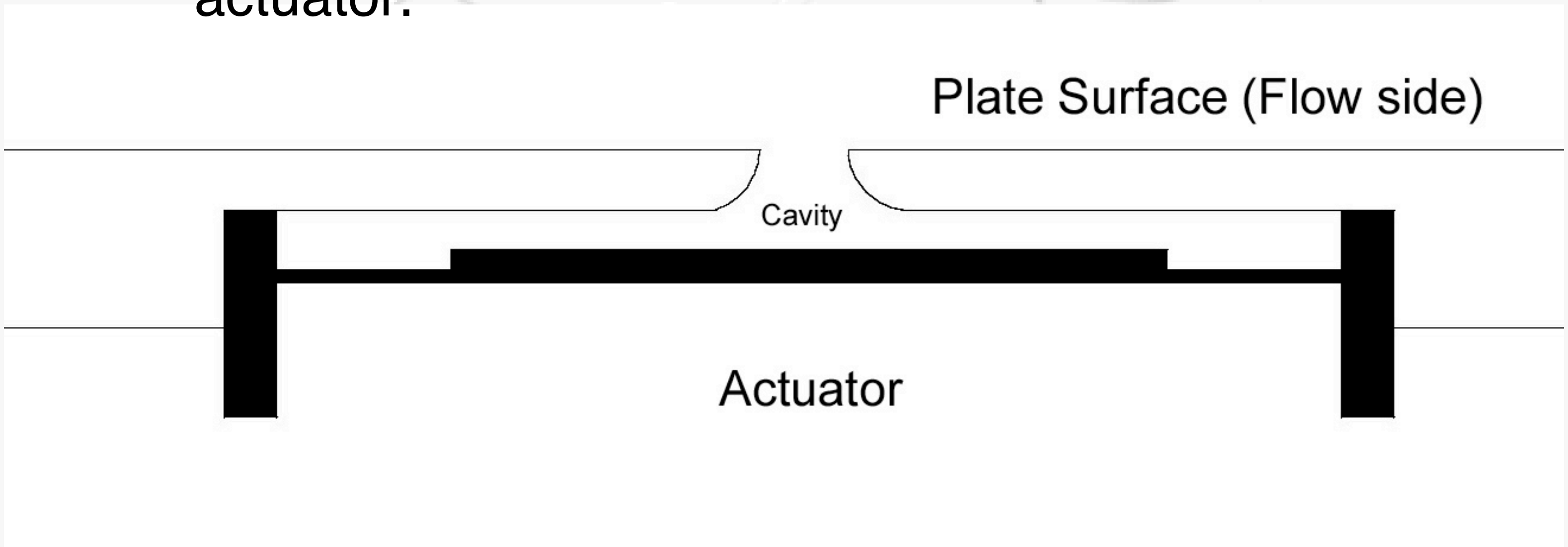


Jet Parameters:

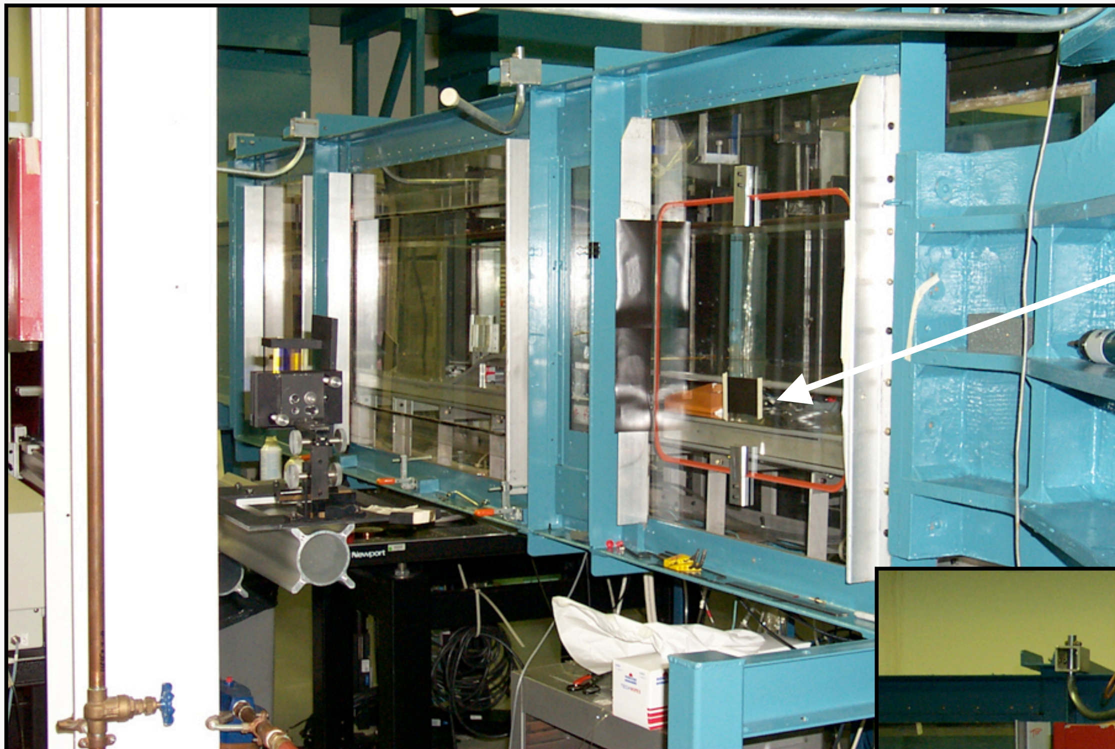
- **Cavity Pressure**
- **Diaphragm Displacement**

Overview of Case 2 -- Actuator Details

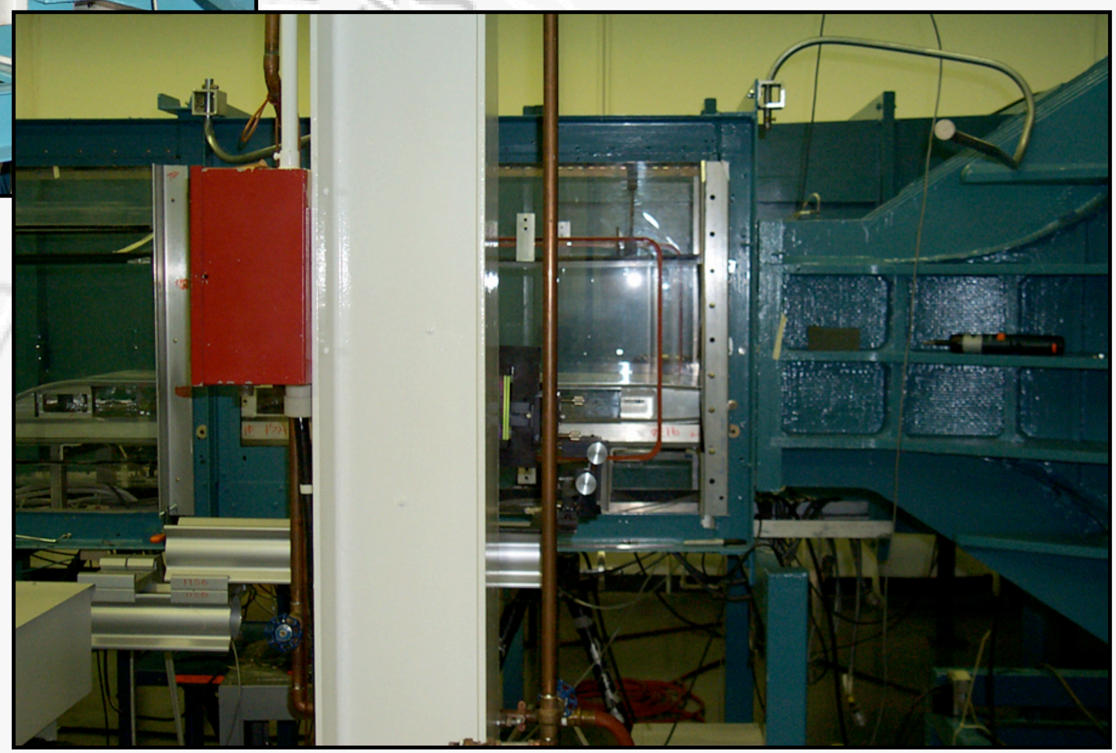
- Actuator wall opposite from the jet exit is flexible and connected to an electromechanically driven piston.
- The diaphragm (wall) is driven at 150 Hz.
- Actuator is internally instrumented:
  - differential pressure transducer
  - an absolute pressure transducer
  - Thermocouple
  - Diaphragm displacement is measure externally from the actuator.



15 inch Low Speed Wind Tunnel



- Optical Quality Glass Windows installed in both test section bays
- Closed-return atmospheric facility



- Jet installed into an existing flat plate model.
- Tunnel ceiling was adjusted to yield a zero pressure gradient along plate.

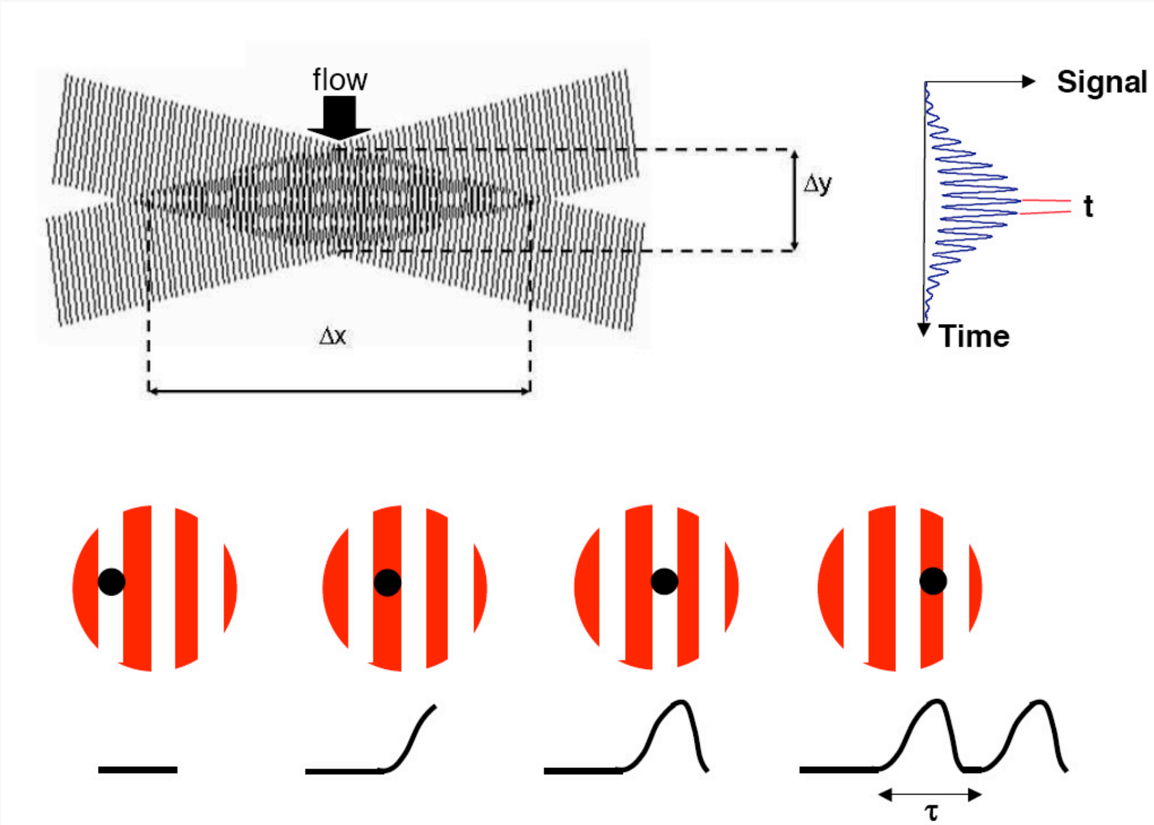
Measurement Systems Utilized in Case 2

The two measurement systems utilized in Case 2 for the flowfield measurements were:

- Laser Doppler Velocimetry (LDV) (3 Component)
  - Velocity Profiles
  - Single Point Measurement

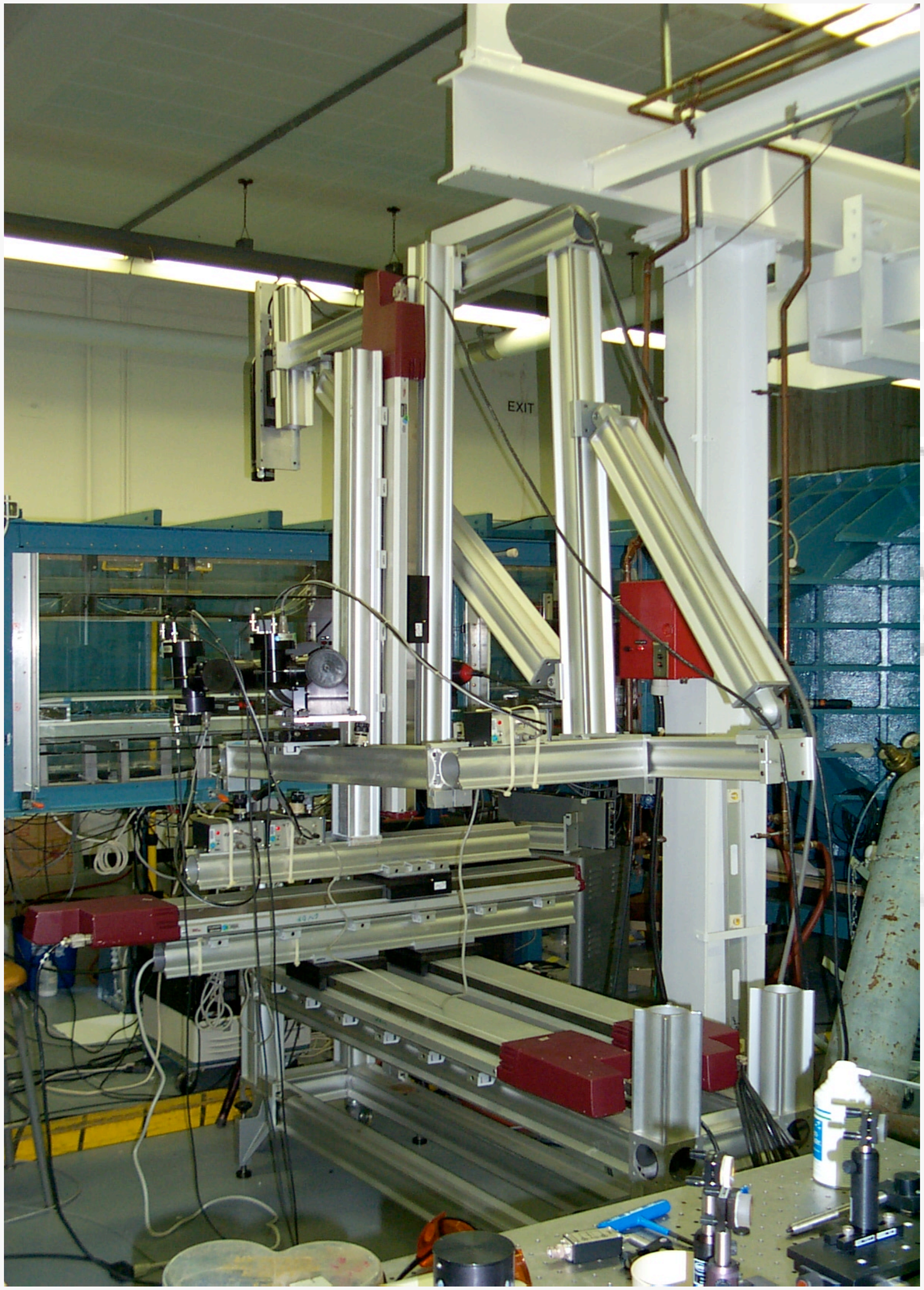
- Particle Image Velocimetry (PIV)
  - Two types: Stereo (3C) and 2-D (2C)
(SPIV) (2D-PIV)
  - Measures Velocity field in a Plane

Laser-Doppler Velocimetry (LDV):

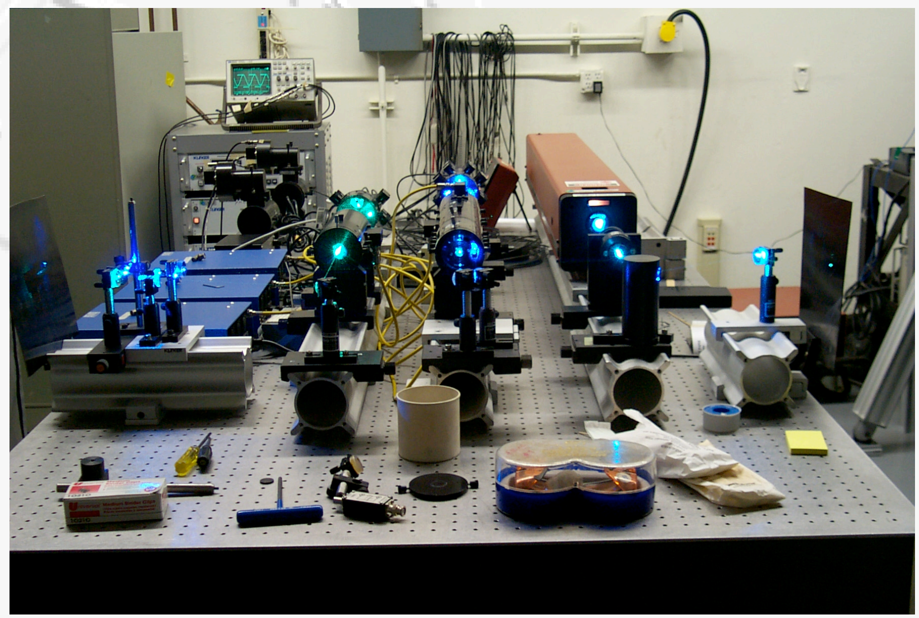


- Tracks particles added to flow (0.86 m Polystyrene Latex(PSL))
- Non Intrusive
- Averages across measurement volume (100 m) - “Point measurement”
- 3-D Coincidence mode allows measurement of all 6 turbulent stress tensor terms

3-D LDV System



- Fiber Optic based system
- 100 micron spherical measurement volume
- Off-axis collection thru 6 inch optics
- 1 meter travel in each direction on 1 μm slides
- Macrodyne FDP 3107 (3)
- Primarily TSI optics

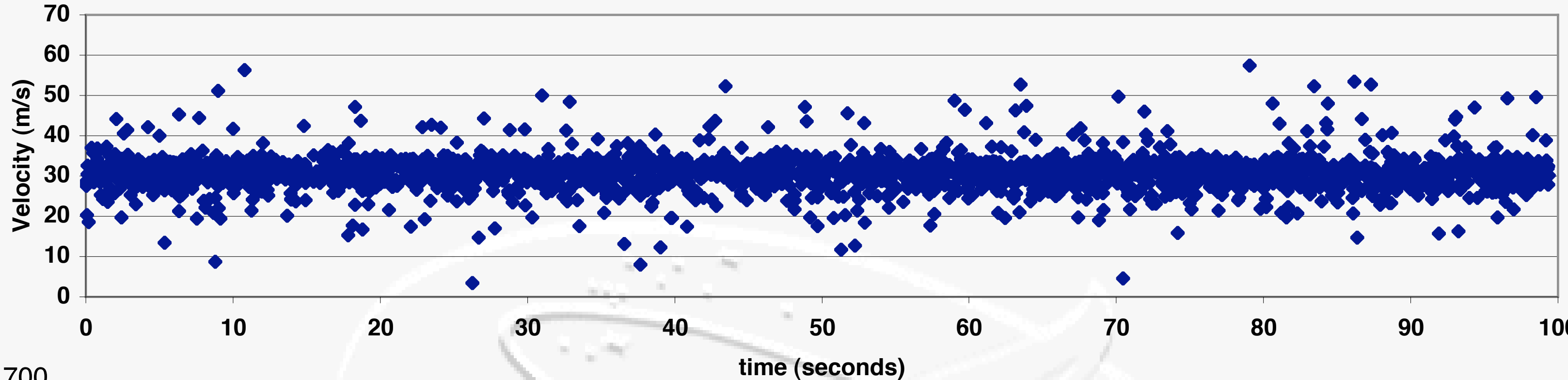


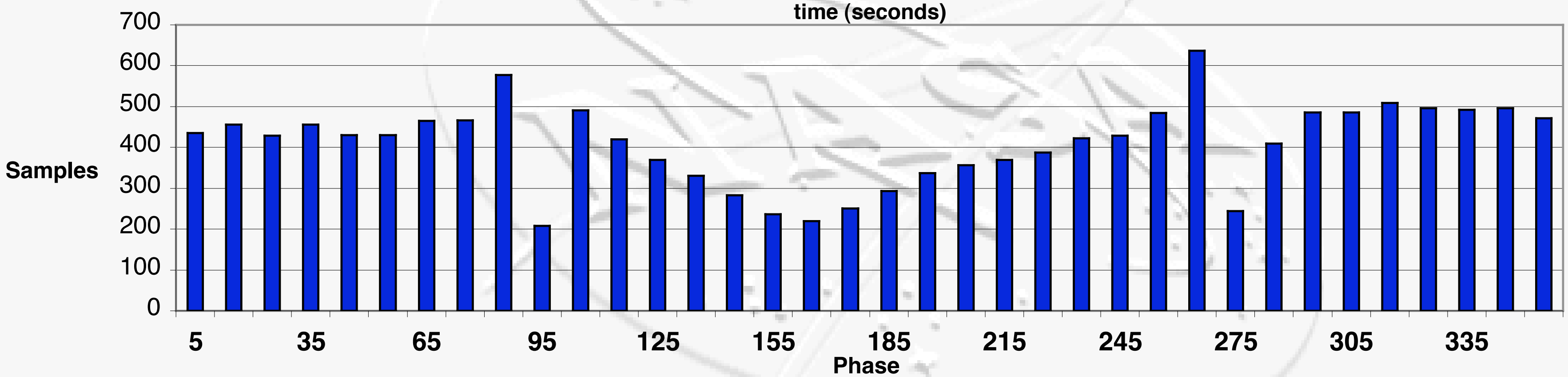
LDV Data Acquisition

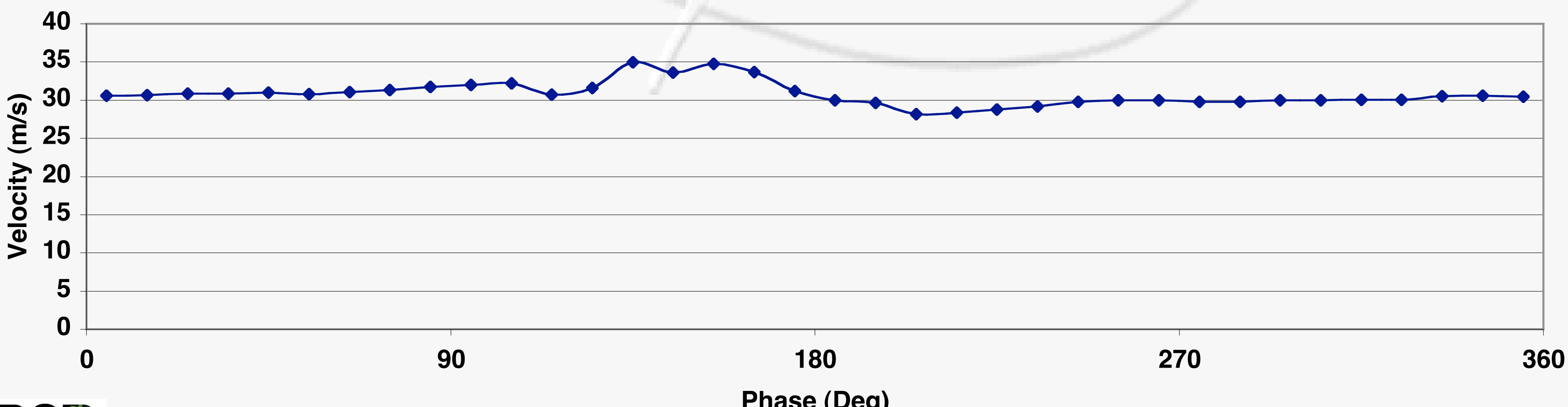
- Minimum 15,000 samples per point.
- Data acquired in coincidence mode
  - need simultaneous valid samples on all 3 components
- Actuator drive signal and a sync signal captured at same instant as velocity data.
- From the drive and sync, the phase angle at the time of acquisition can be calculated.

LDV Post-Processing for Phase-Averaging

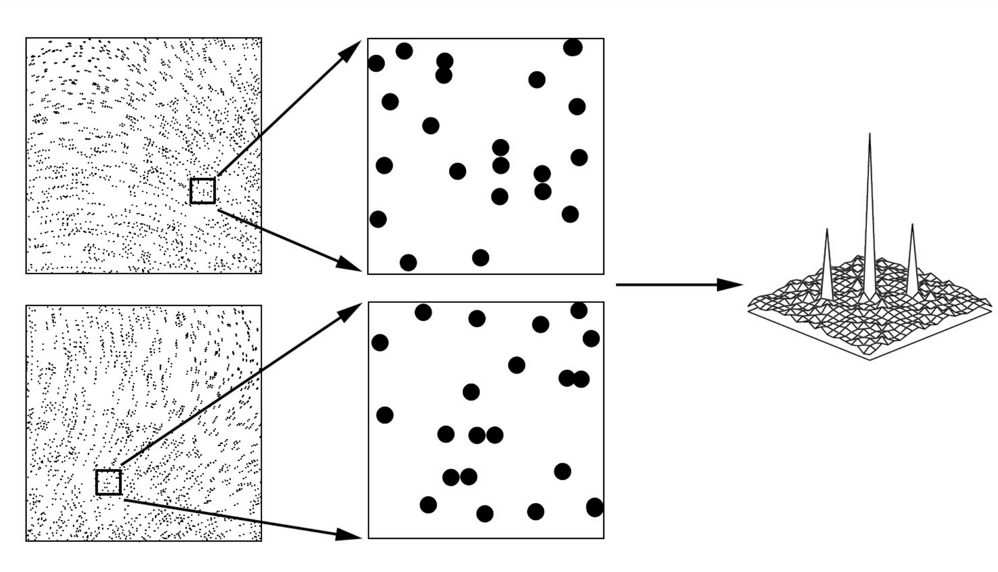
Particle arrival time, actual time of the velocity measurement, occurs randomly.







Particle Image Velocimetry (PIV)

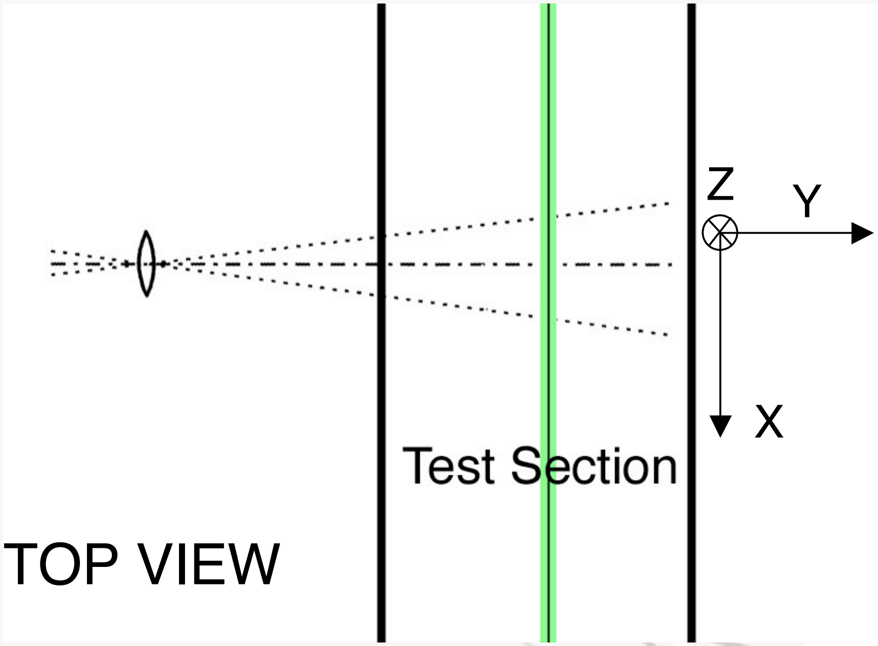


Two images of the seeded flow, separated by a short time interval, are acquired.

Interrogation region determines the spatial resolution. Flow within the interrogation region is represented by a single vector.

- •Tracks particles added to flow (Atomized Mineral Oil (1 m))
- Non Intrusive
- Area Measurement on a plane
- Multiple Components (2D and 3D or Stereo)
- Stereo PIV allows for the measurement of all 6 turbulent stress tensor terms
- Seeding concentration, flare, optical access can all cause problems.
- •With respect to phase, discrete accurate triggers.

2-D and Stereo PIV

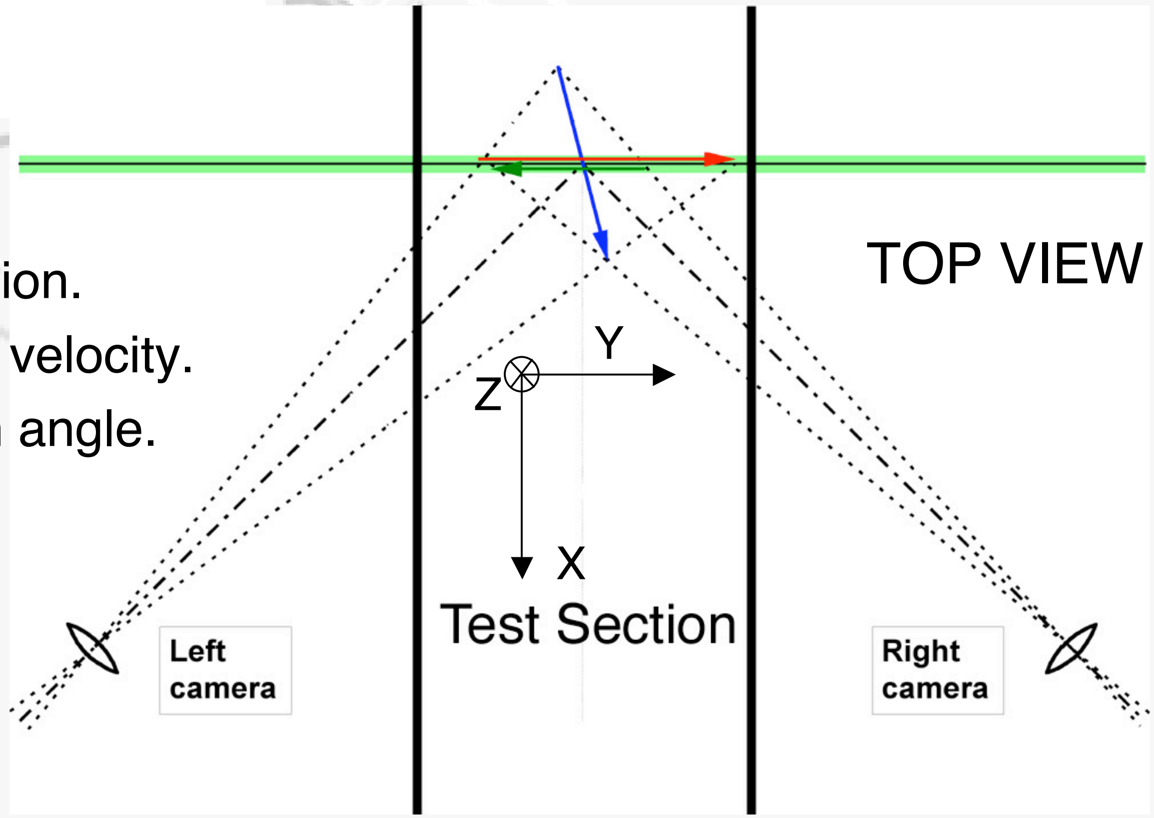


2-D PIV:

- Laser sheet in streamwise direction.
- Measures in-plane velocity components.
- Single camera oriented perpendicular the laser sheet.

Stereo PIV:

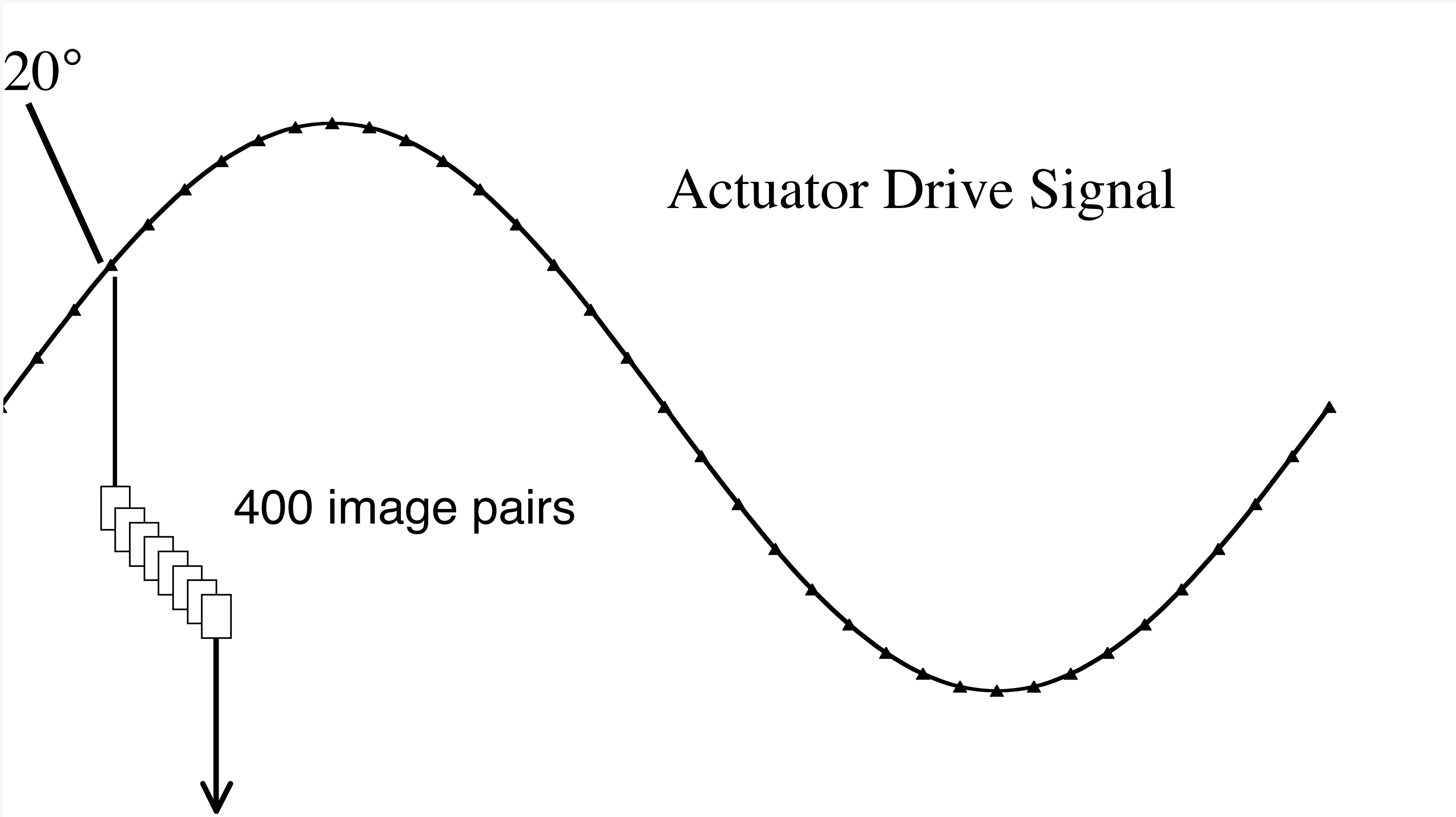
- Laser sheet in spanwise direction.
- Measures all 3 components of velocity.
- Two cameras view sheet at an angle.



PIV Data Acquisition and Post-Processing

- Both PIV systems utilized cameras with 1008x1018 pixel resolution and 105 mm optics.
- A pulsed, frequency-doubled, 300 mJ Nd-YAG laser operating at 10 Hertz provided the laser light.
- The same sync signal used in the LDV portion of the experiment was used to sync the PIV image acquisition.
- A timing delay from the start of the sync allows the PIV images to be acquired at a specific phase angle.
- 400 instantaneous velocity fields were measured then averaged to yield the phase-averaged data.
- Data for 36 phase angles, every 10°, was acquired.
- Timing, Laser triggering, Image acquisition, and data reduction were all performed using a commercial system.

PIV Data Acquisition and Post-Processing



Phase-Averaged velocity field for 20º

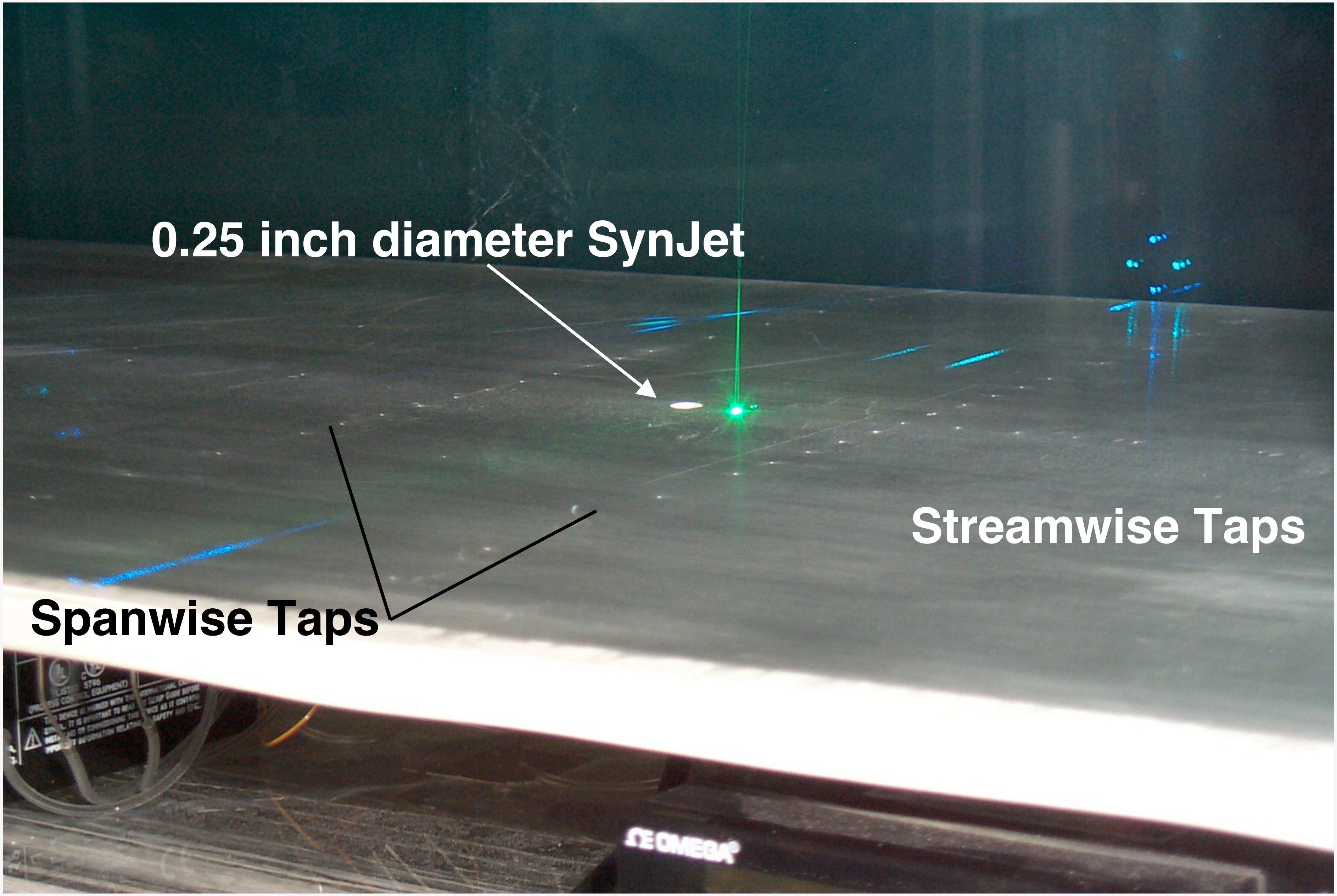
37 phase angles and baseline, 300 images x 2 → 44 Gb of Image data

400 images x 1 → 30 Gb of Image data

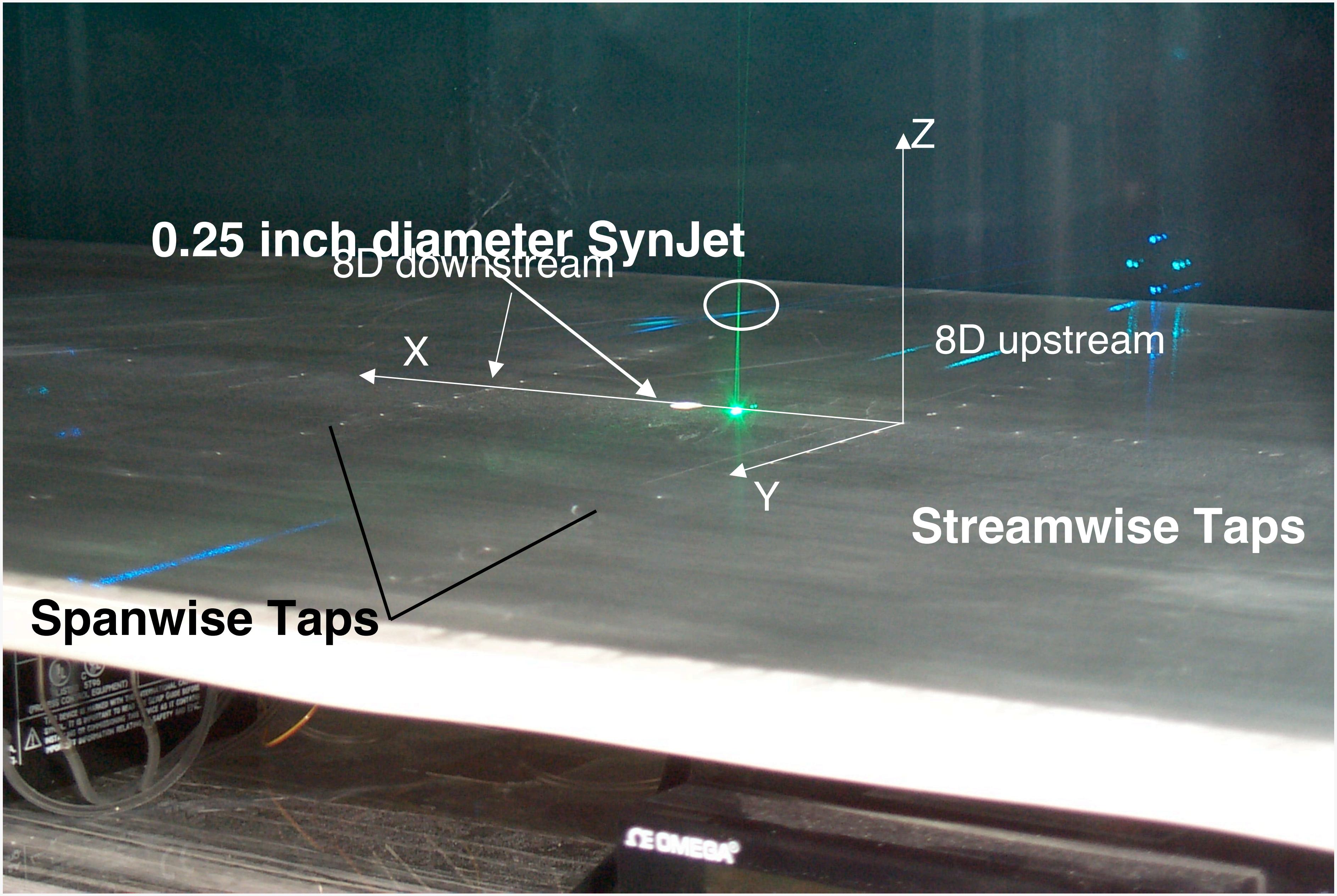
Specification of the Boundary Conditions

- Streamwise Pressure Gradient
- Upstream boundary layer profile (UBC)
- Actuator parameters as a function of Phase
  - Diaphragm Displacement
  - Cavity Pressure
  - Cavity Temperature

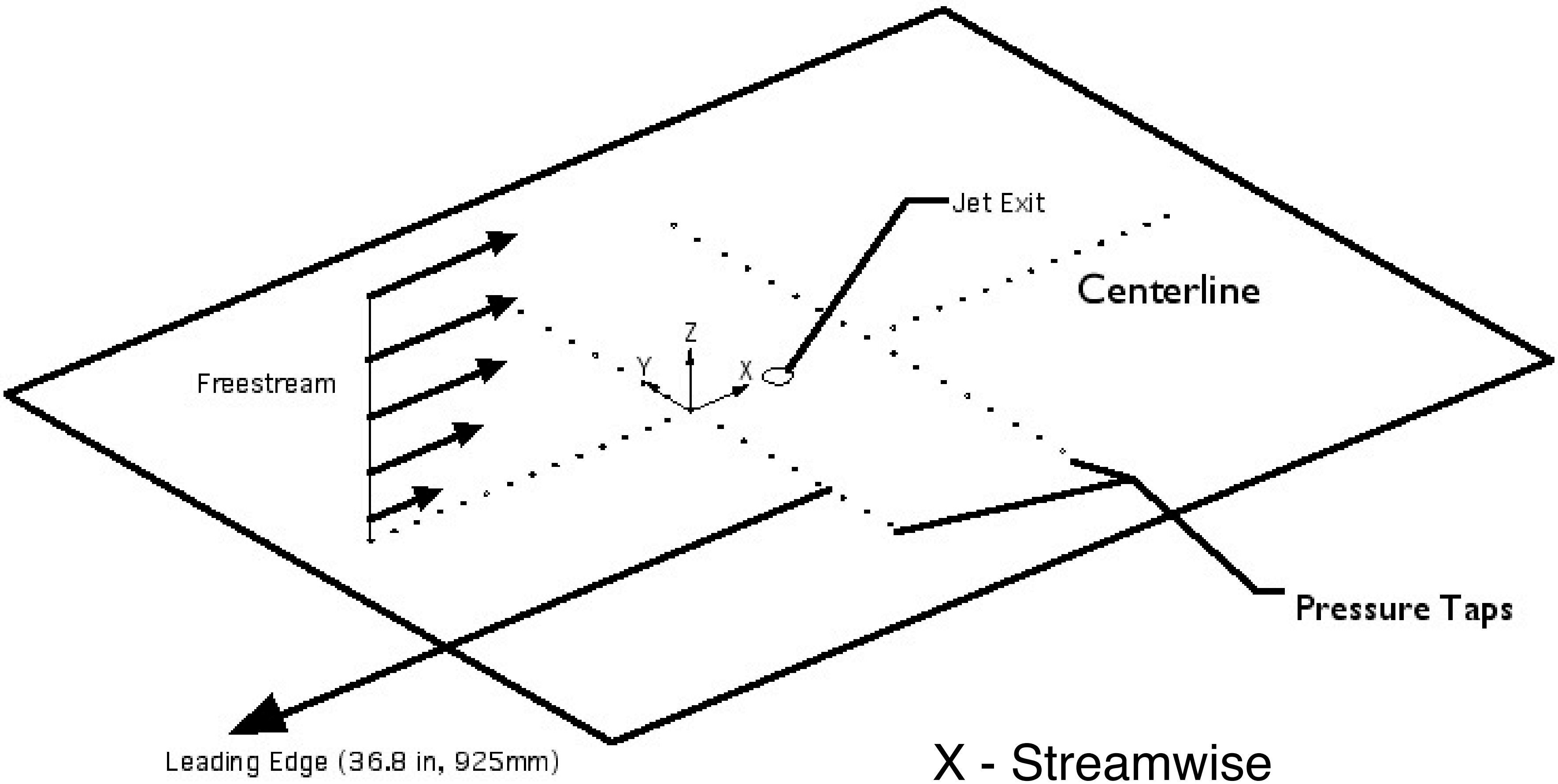
Splitter plate as installed in the 15 Inch LSWT



Coordinate System Utilized in Case 2

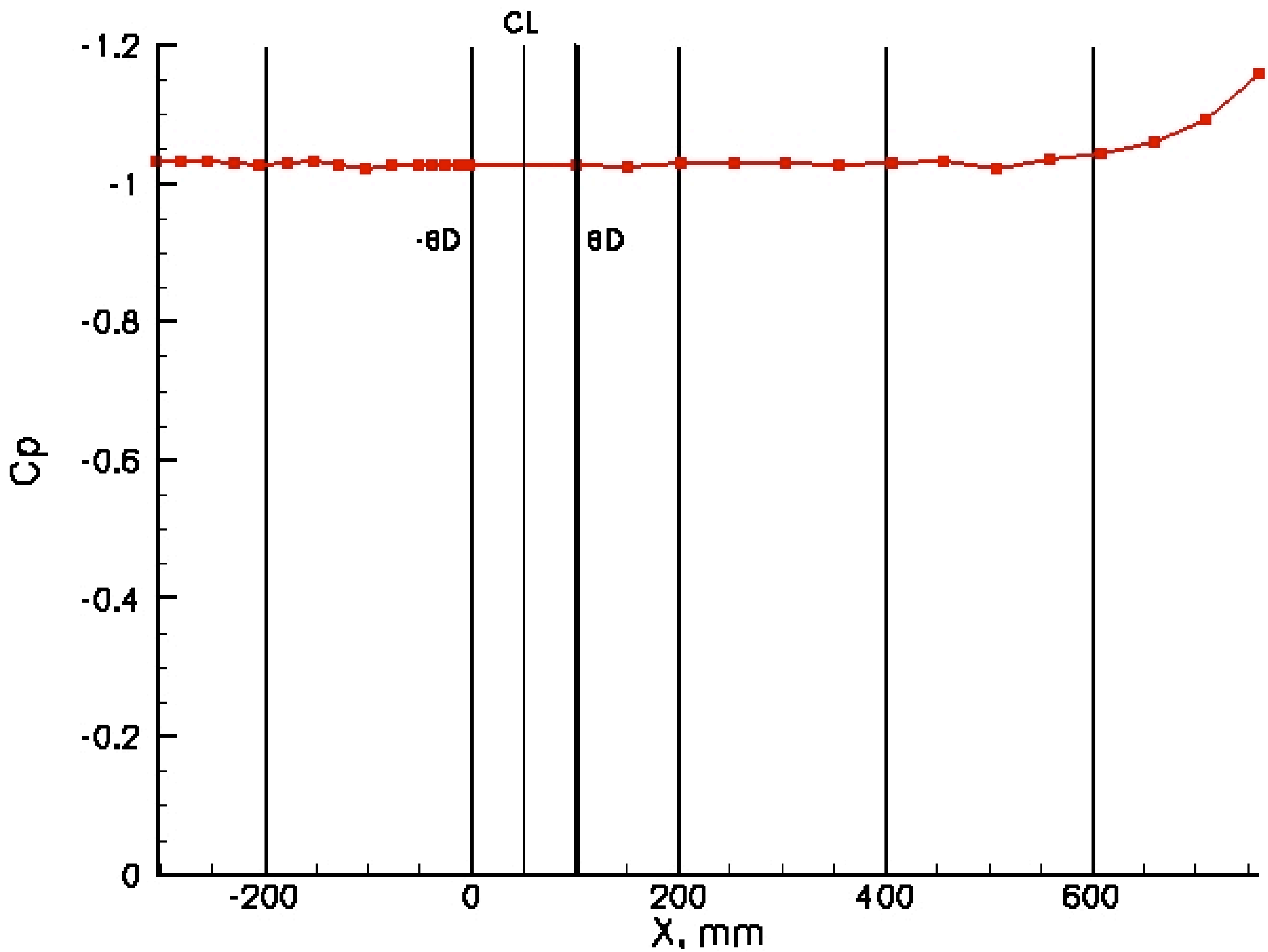


Model Coordinate System

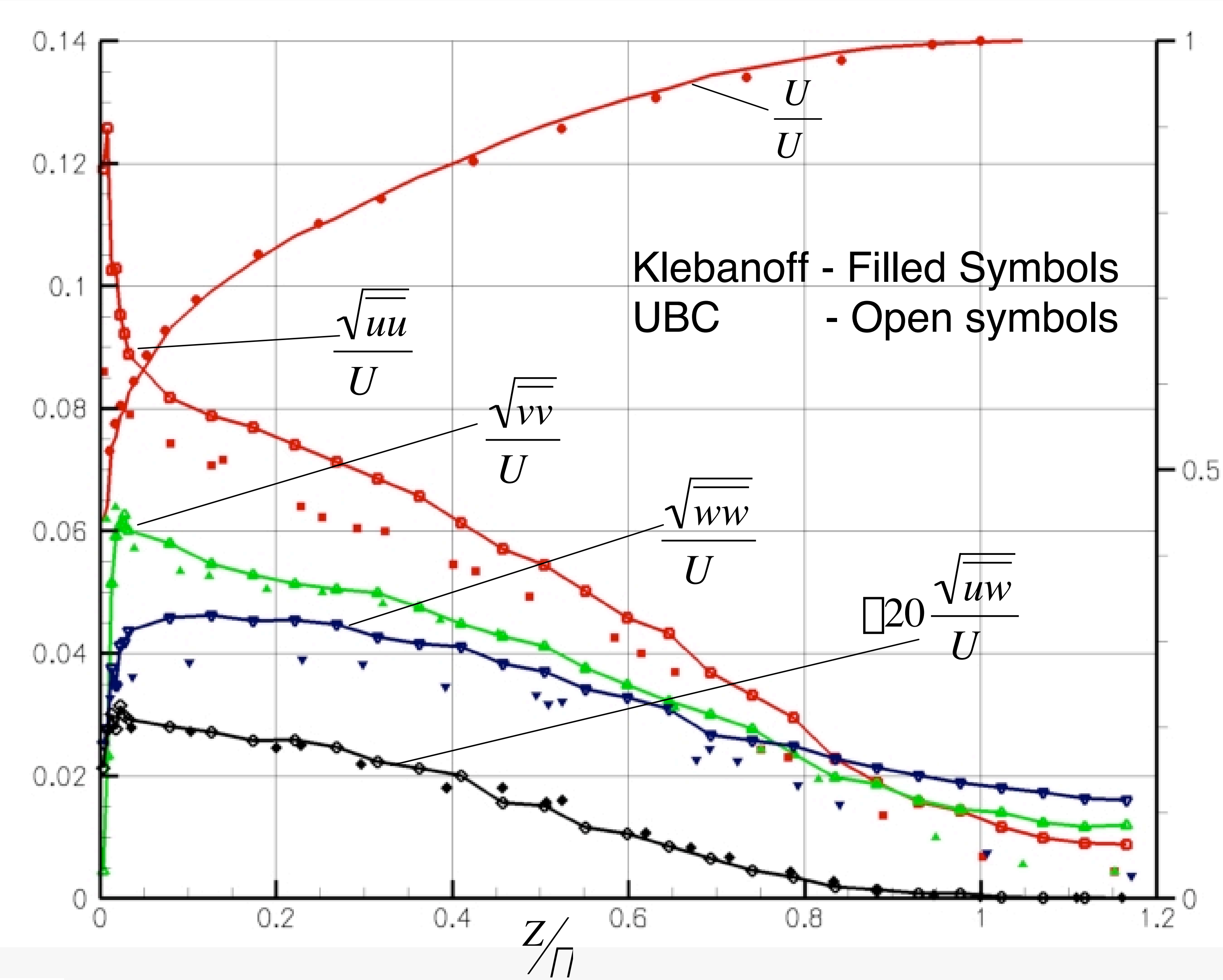


X - Streamwise
Y - Spanwise
Z - Vertical

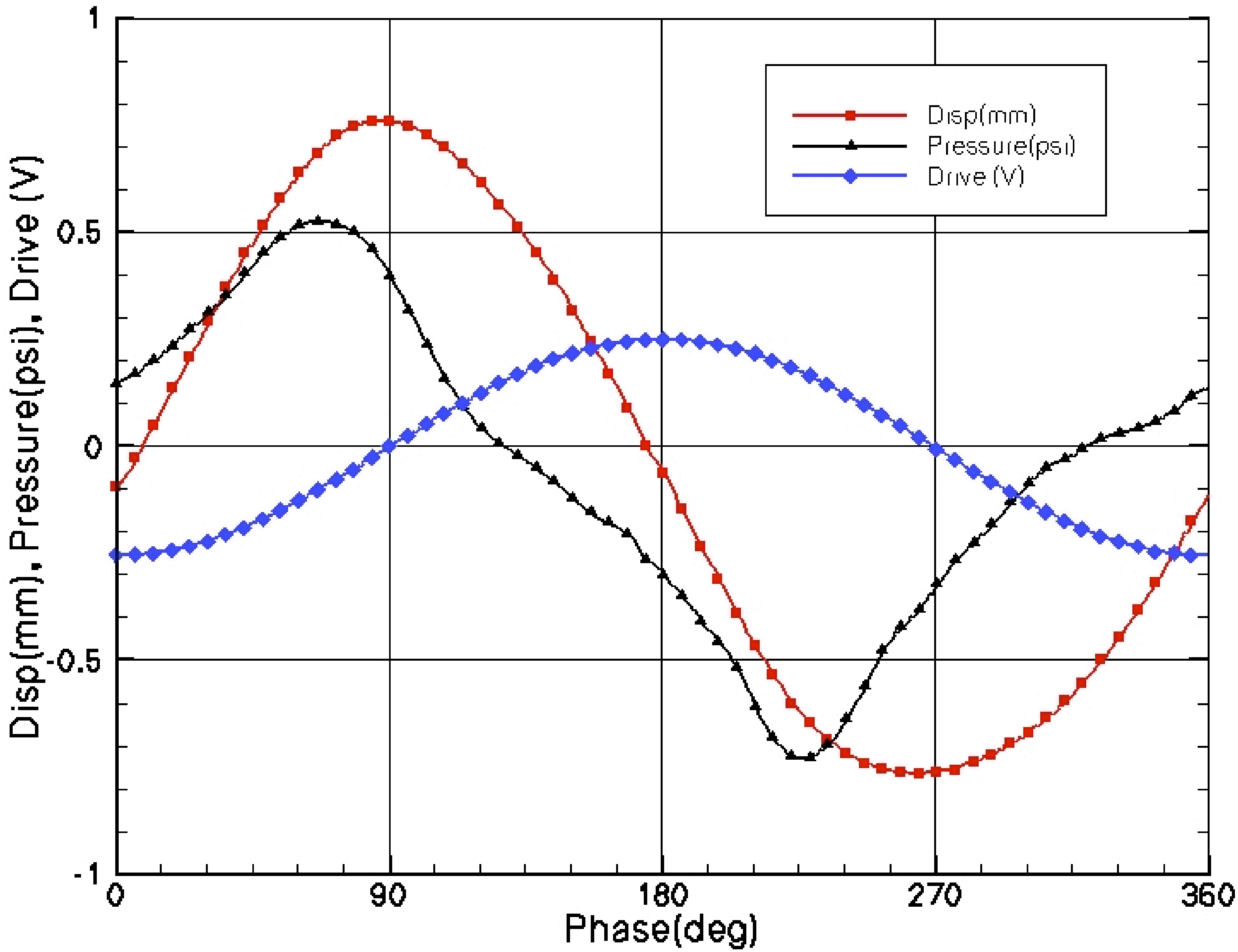
Tunnel Streamwise Pressure Gradient



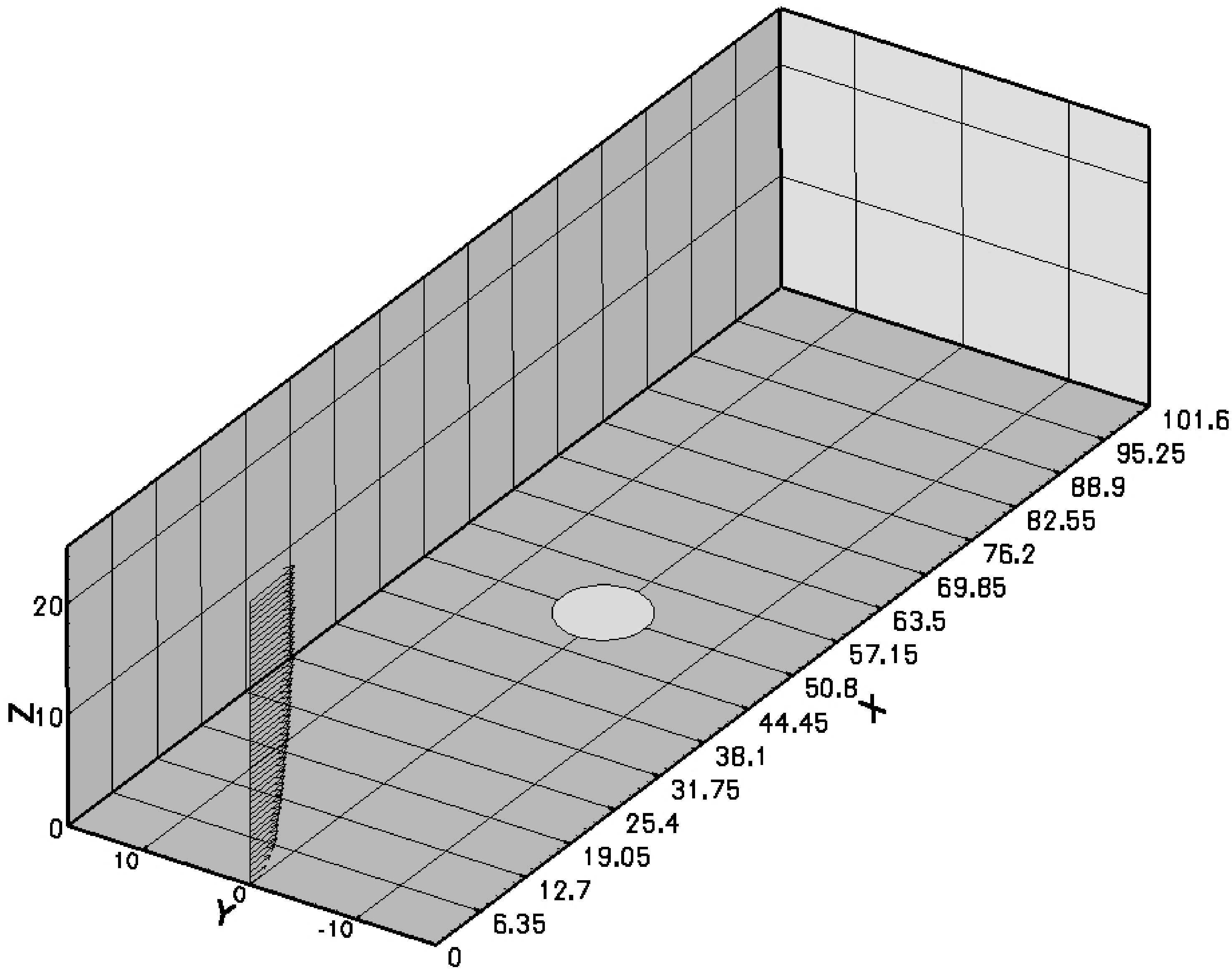
Comparison of the UBC and the data of Klebanoff



Actuator parameters as a function of Phase



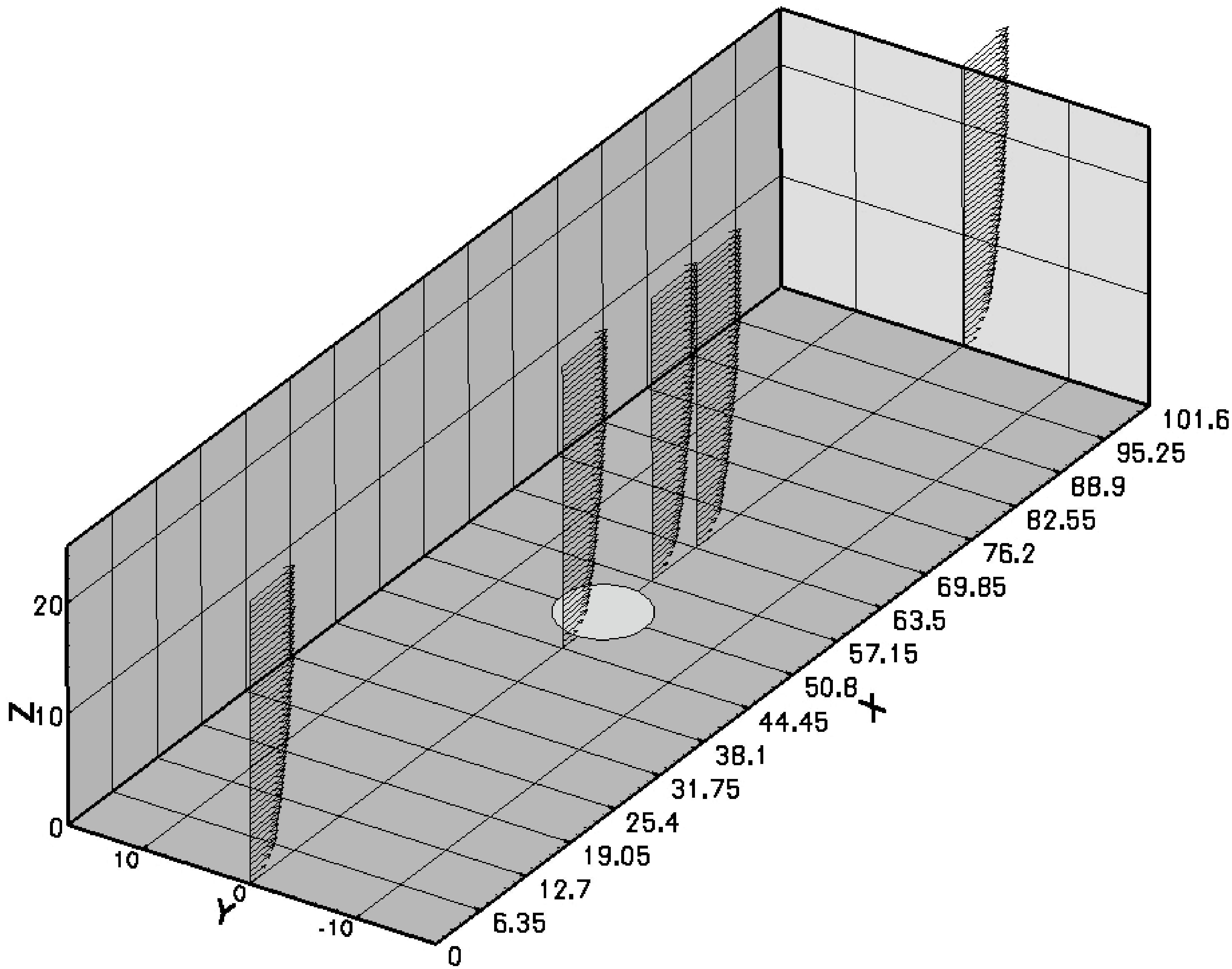
Measurement Systems by Location



LDV:

- UBC

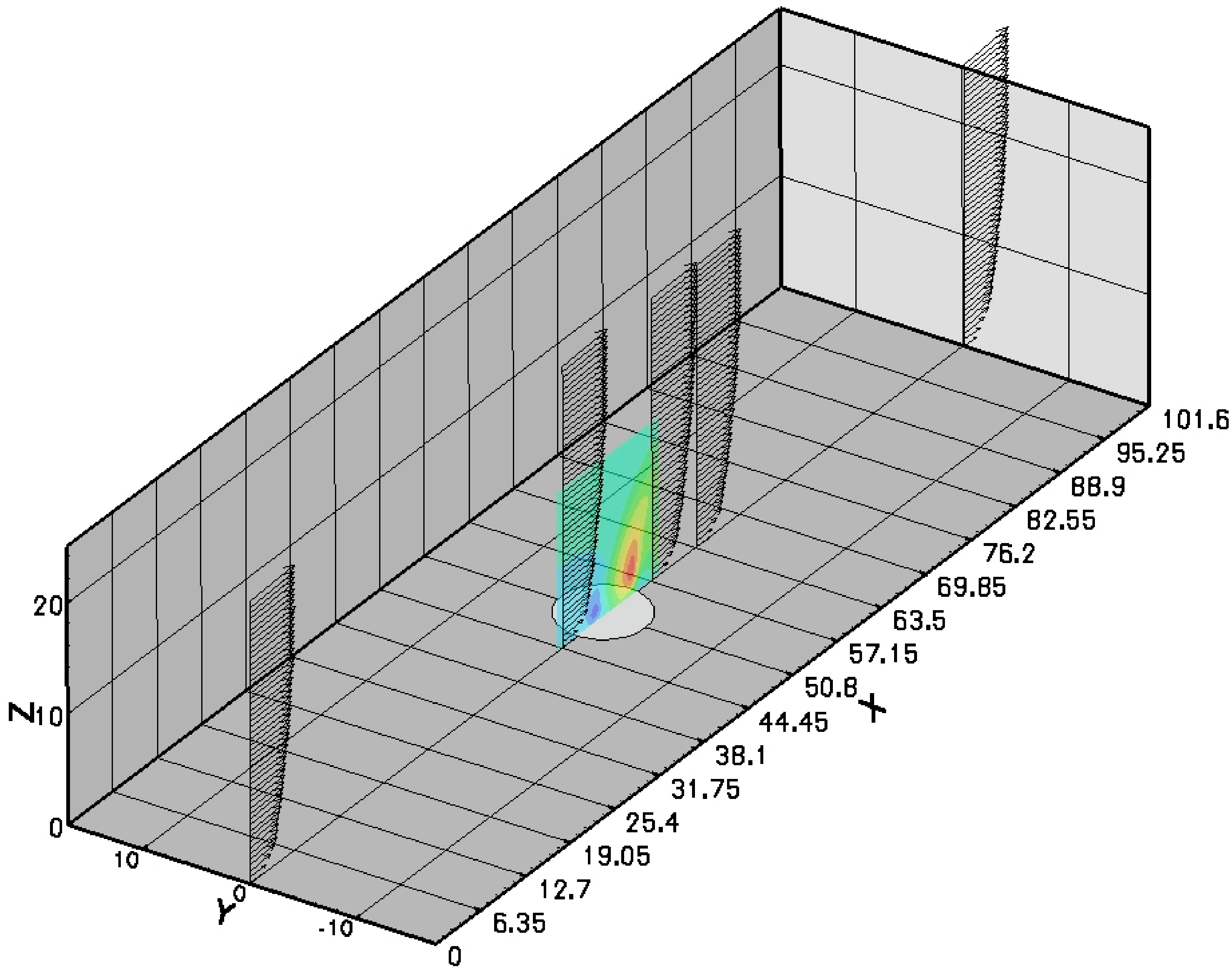
Measurement Systems by Location



LDV:

- UBC
- -1D
- +1D
- +2D
- +8D
- Exit, z=10

Measurement Systems by Location



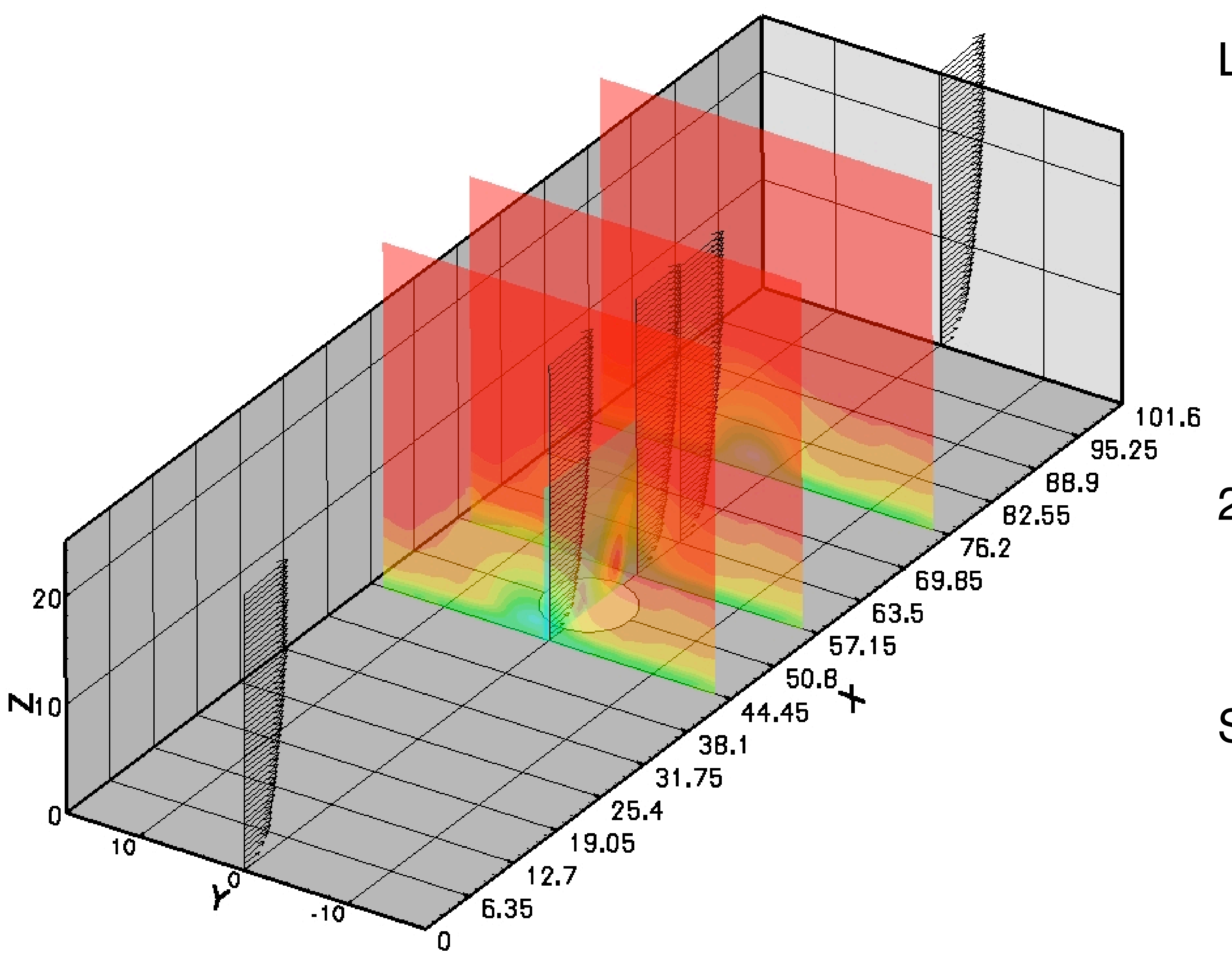
LDV:

- UBC
- -1D
- +1D
- +2D
- +8D
- Exit, z=10

2-D PIV:

- Streamwise (Y=0)

Measurement Systems by Location



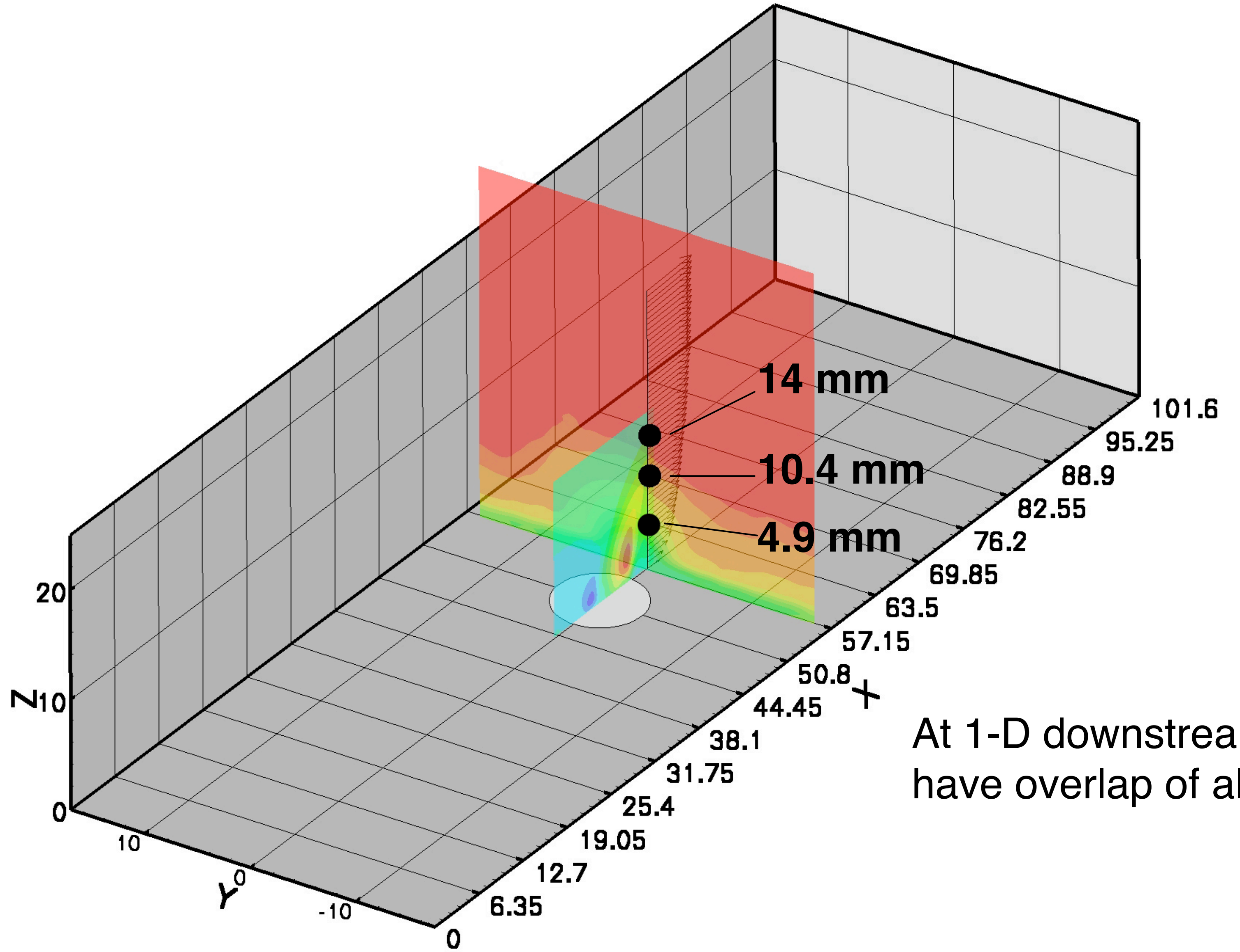
LDV:
- UBC
- -1D
- +1D
- +2D
- +8D
- Exit, z=10

2-D PIV:
- Streamwise (Y=0)

Stereo PIV:
- -1D
- +1D
- +4D

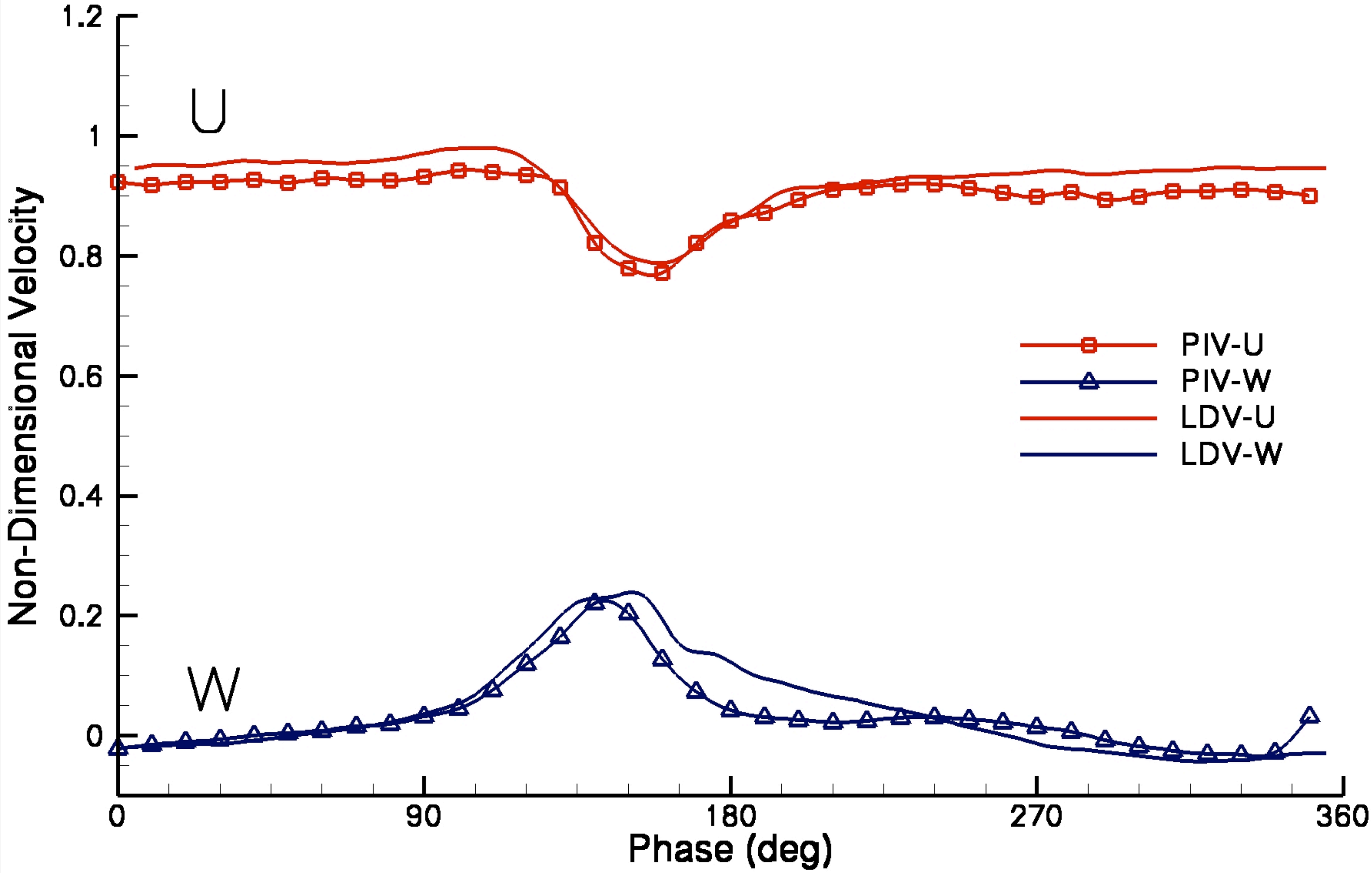
(Spanwise)

Relative Accuracy of the Measurement Systems

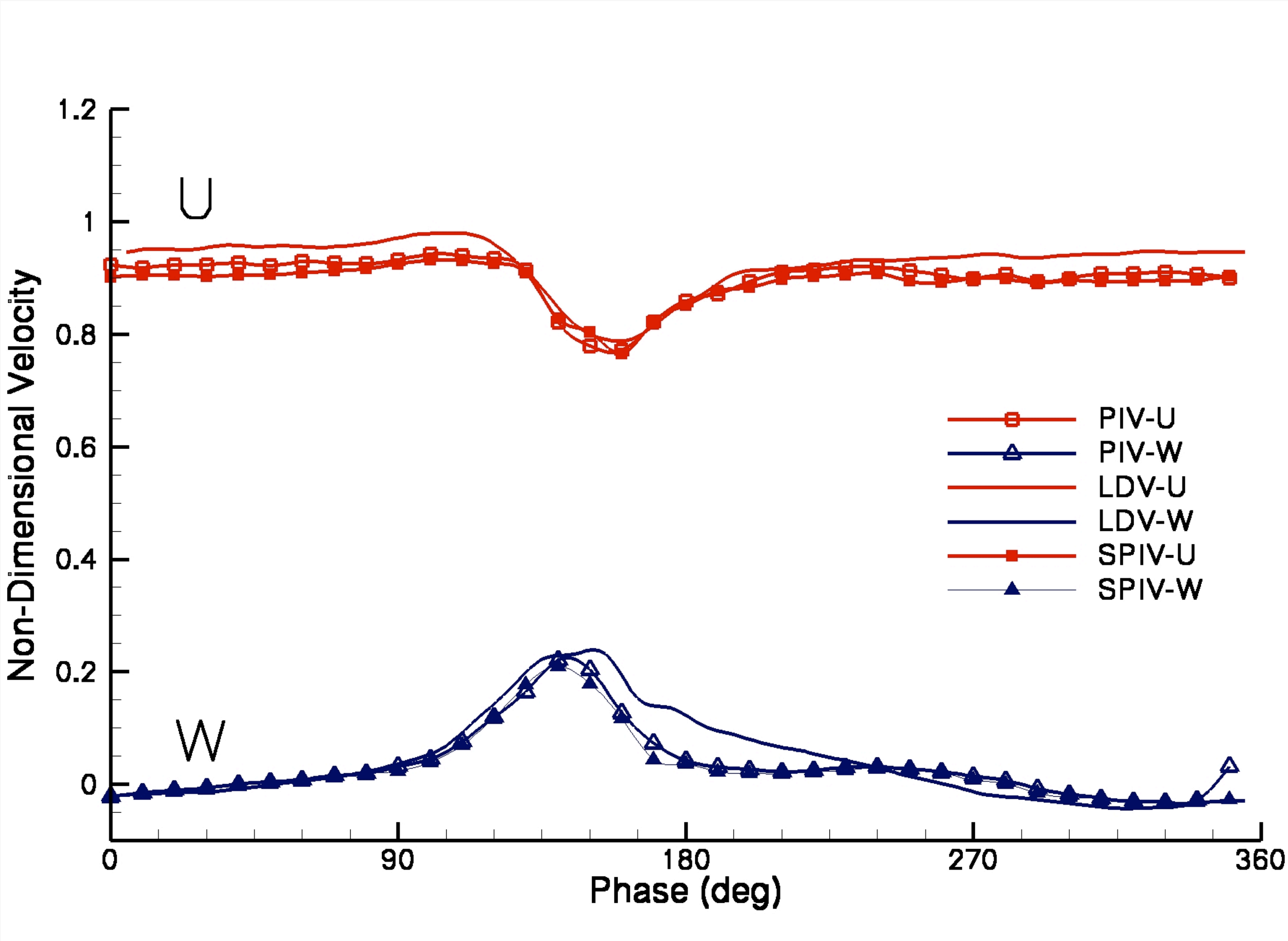


At 1-D downstream (x=57.15 mm), have overlap of all three systems

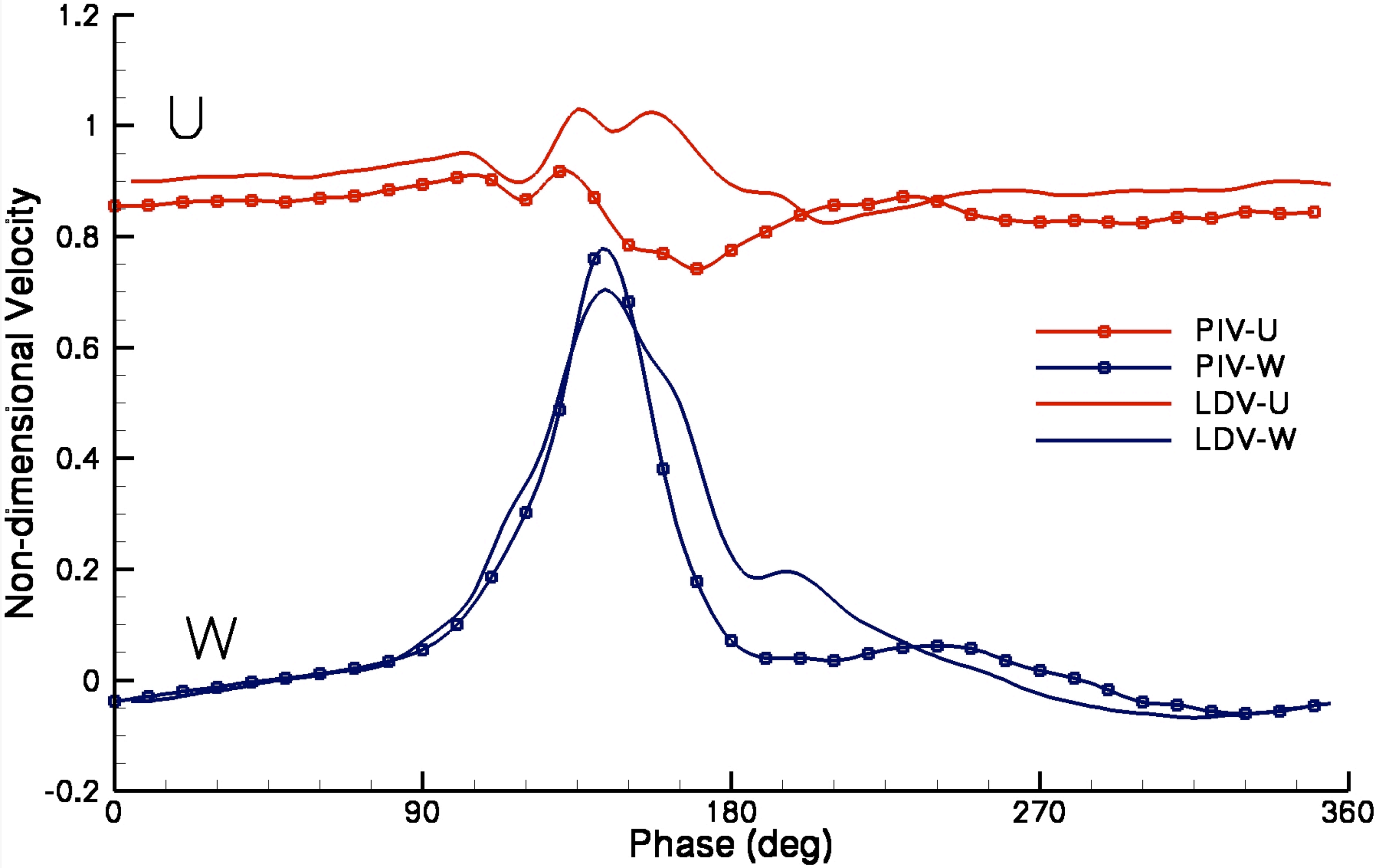
Velocity Signature Comparison at (57.15, 0, 14.0)



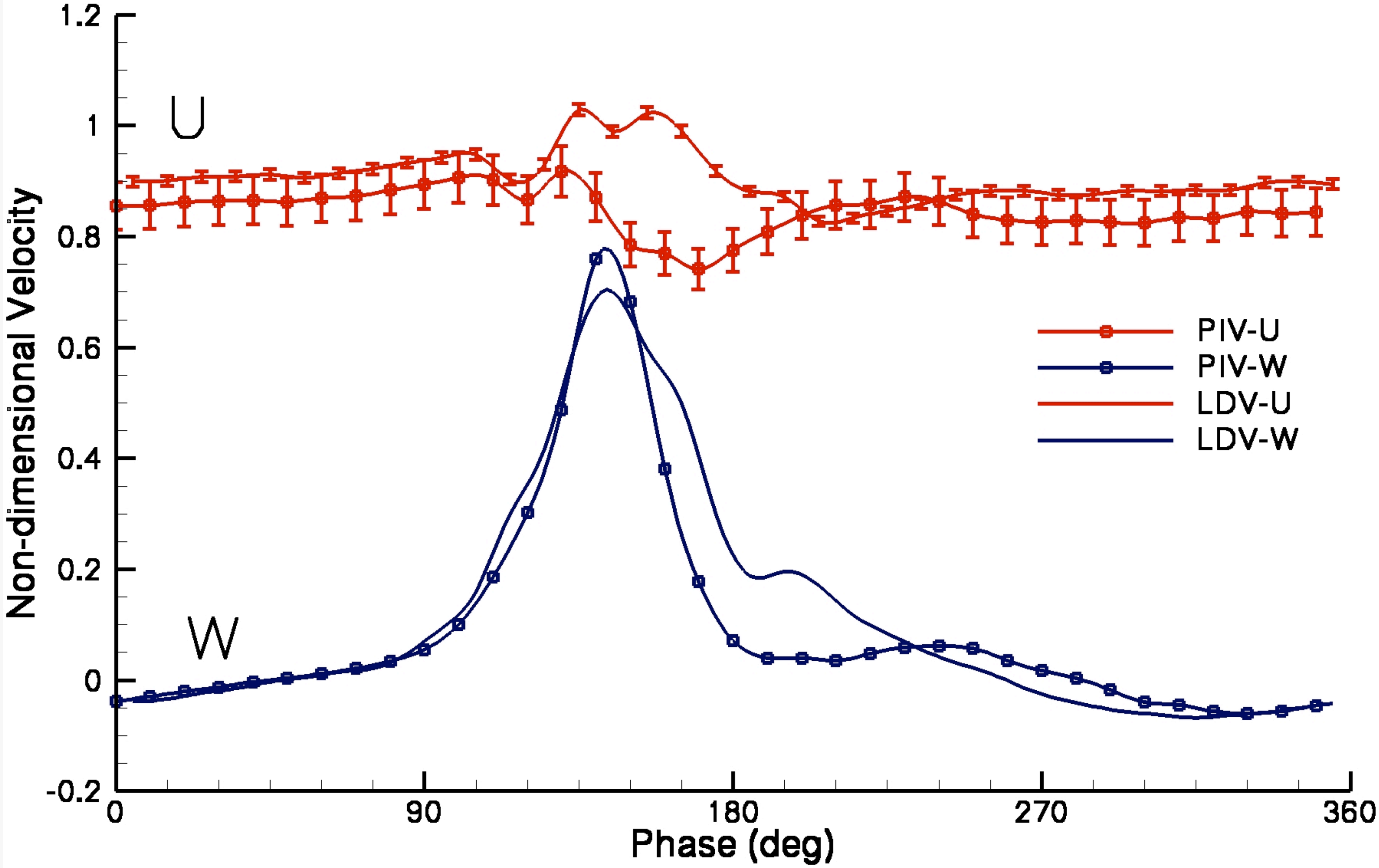
Velocity Signature Comparison at (57.15, 0, 14.0)



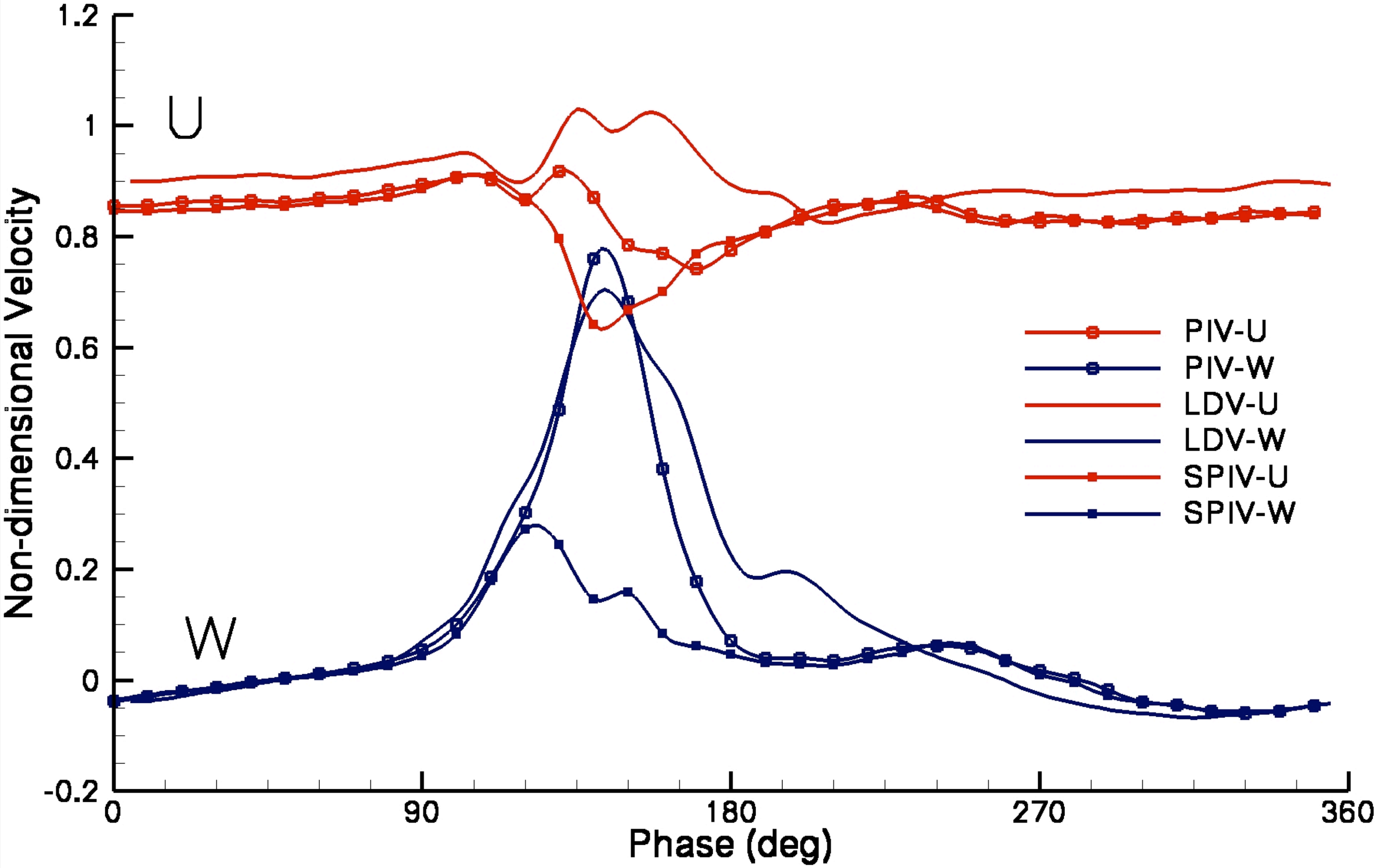
Velocity Signature Comparison at (57.15, 0, 10.4)



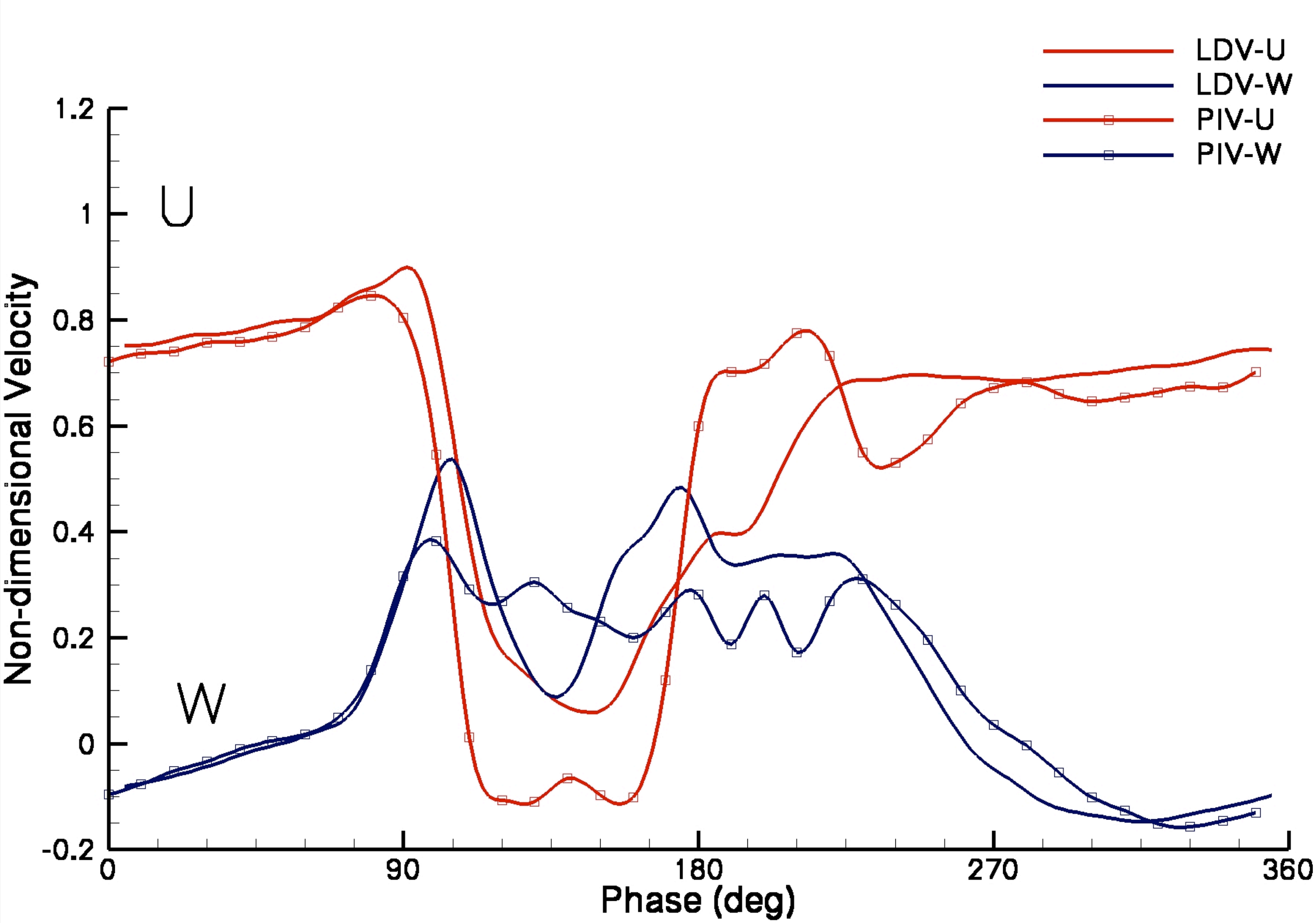
Velocity Signature Comparison at (57.15, 0, 10.4)



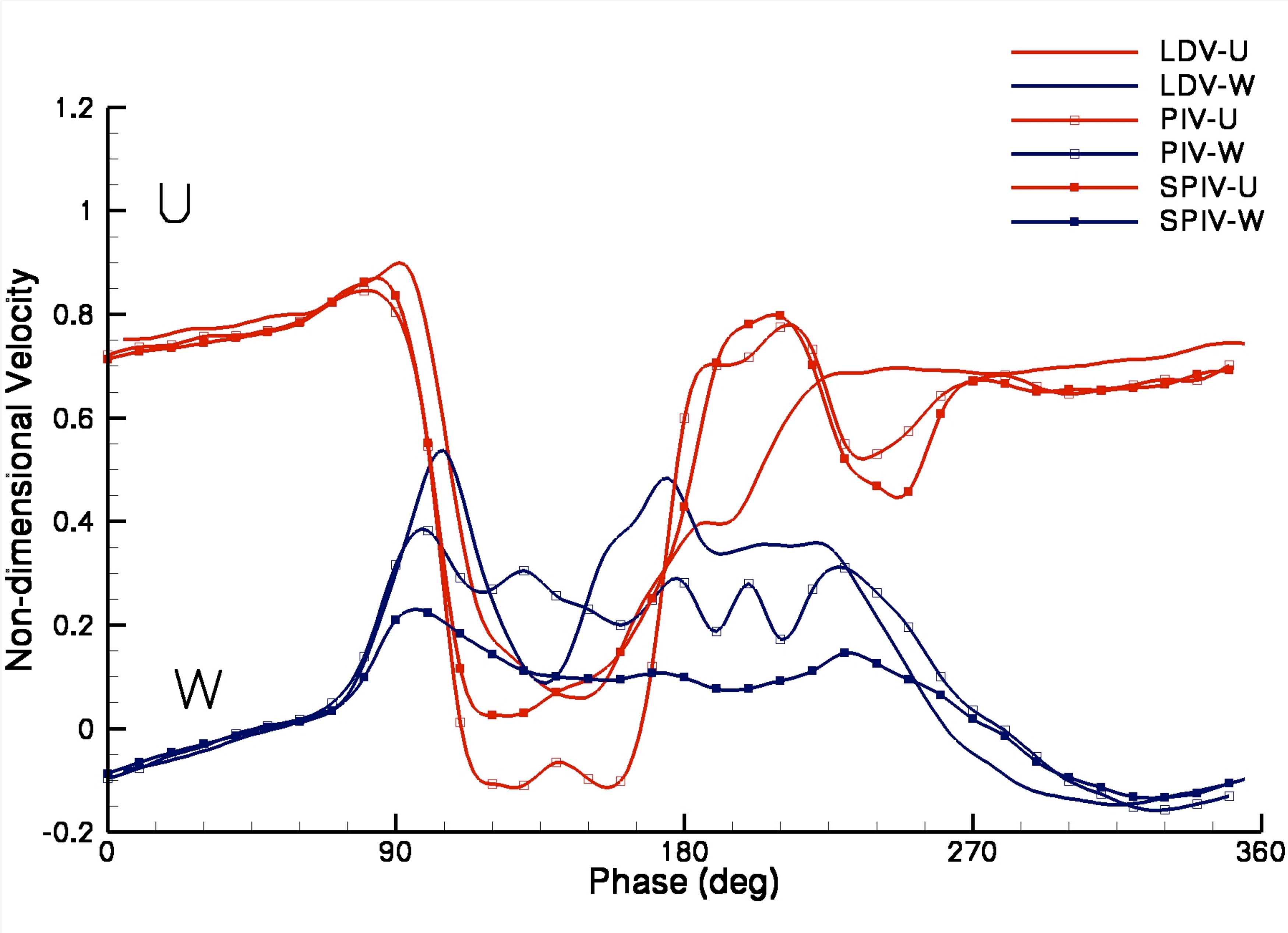
Velocity Signature Comparison at (57.15, 0, 10.4)



Velocity Signature Comparison at (57.15, 0, 4.9)



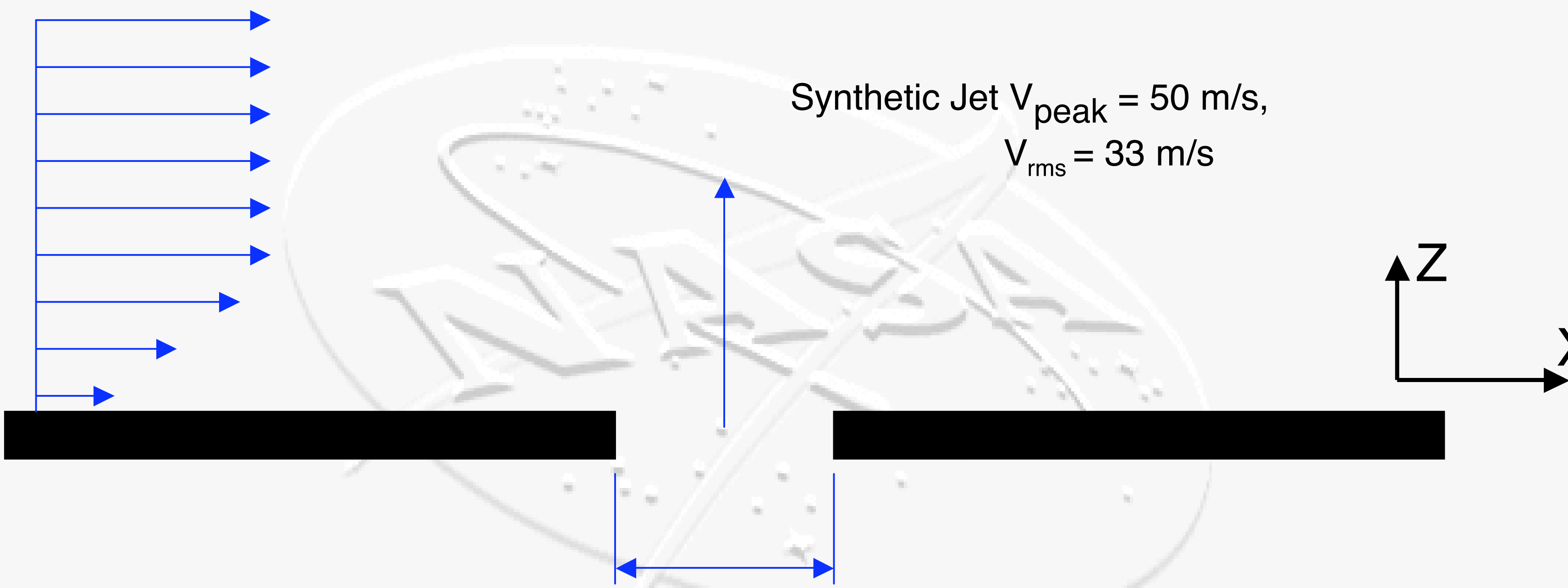
Velocity Signature Comparison at (57.15, 0, 4.9)



Phase-Averaged LDV Measurements

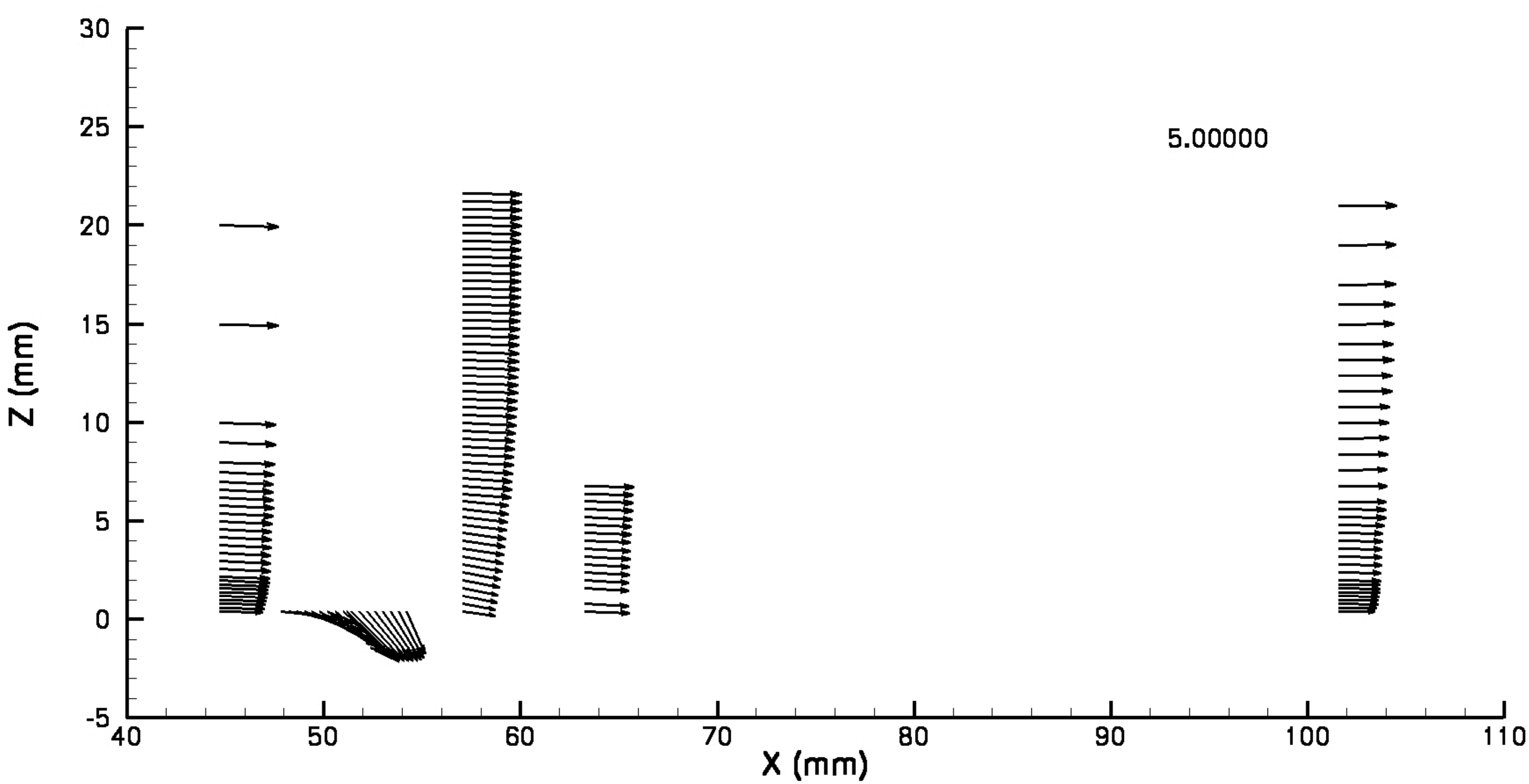
Freestream -- Turbulent Boundary Layer, □ = 21 mm

Mach Number, M = 0.10 (U = 34 m/s)

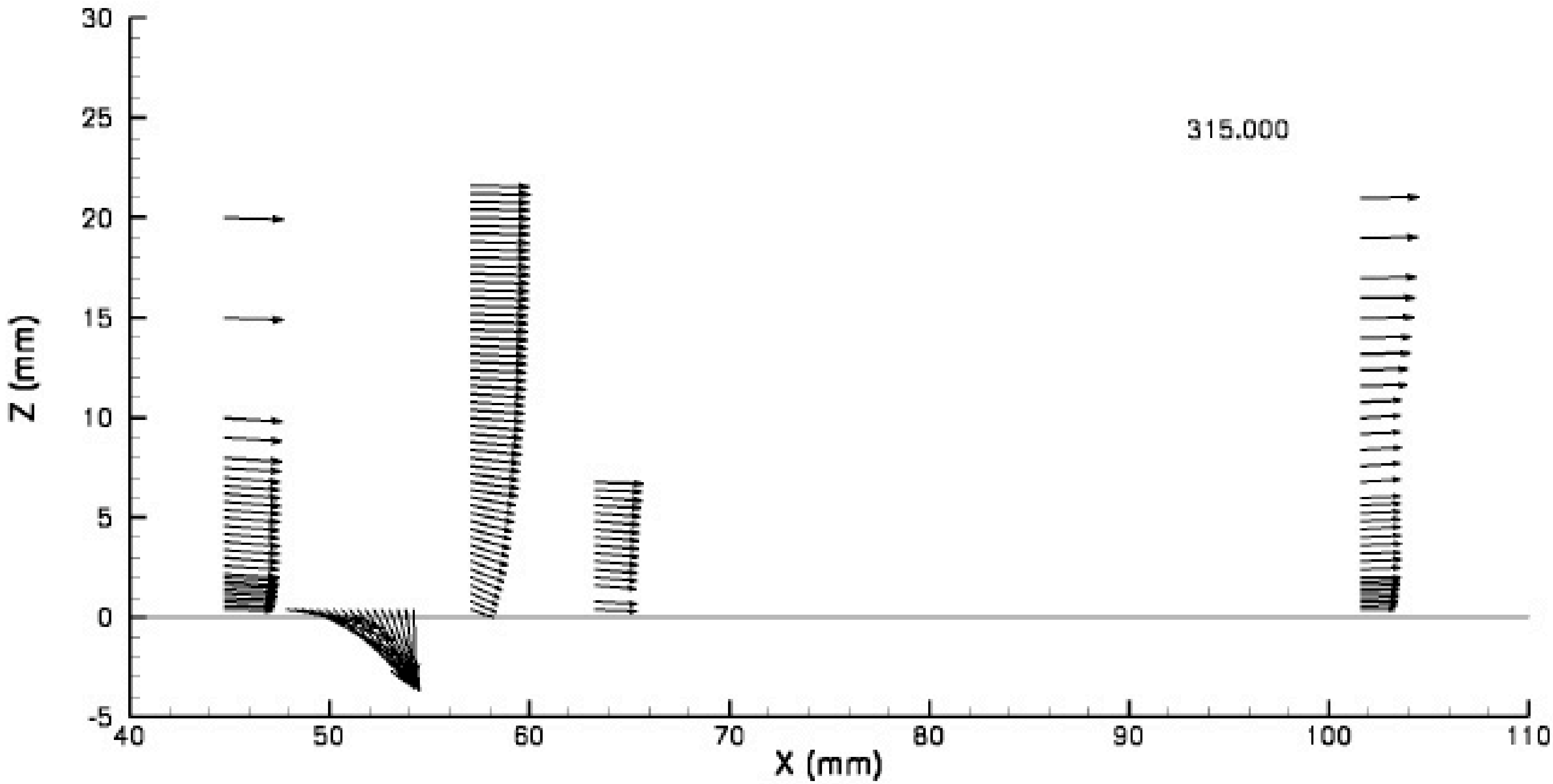


D_j = 6.4 mm (0.25 inches)
Jet Diameter

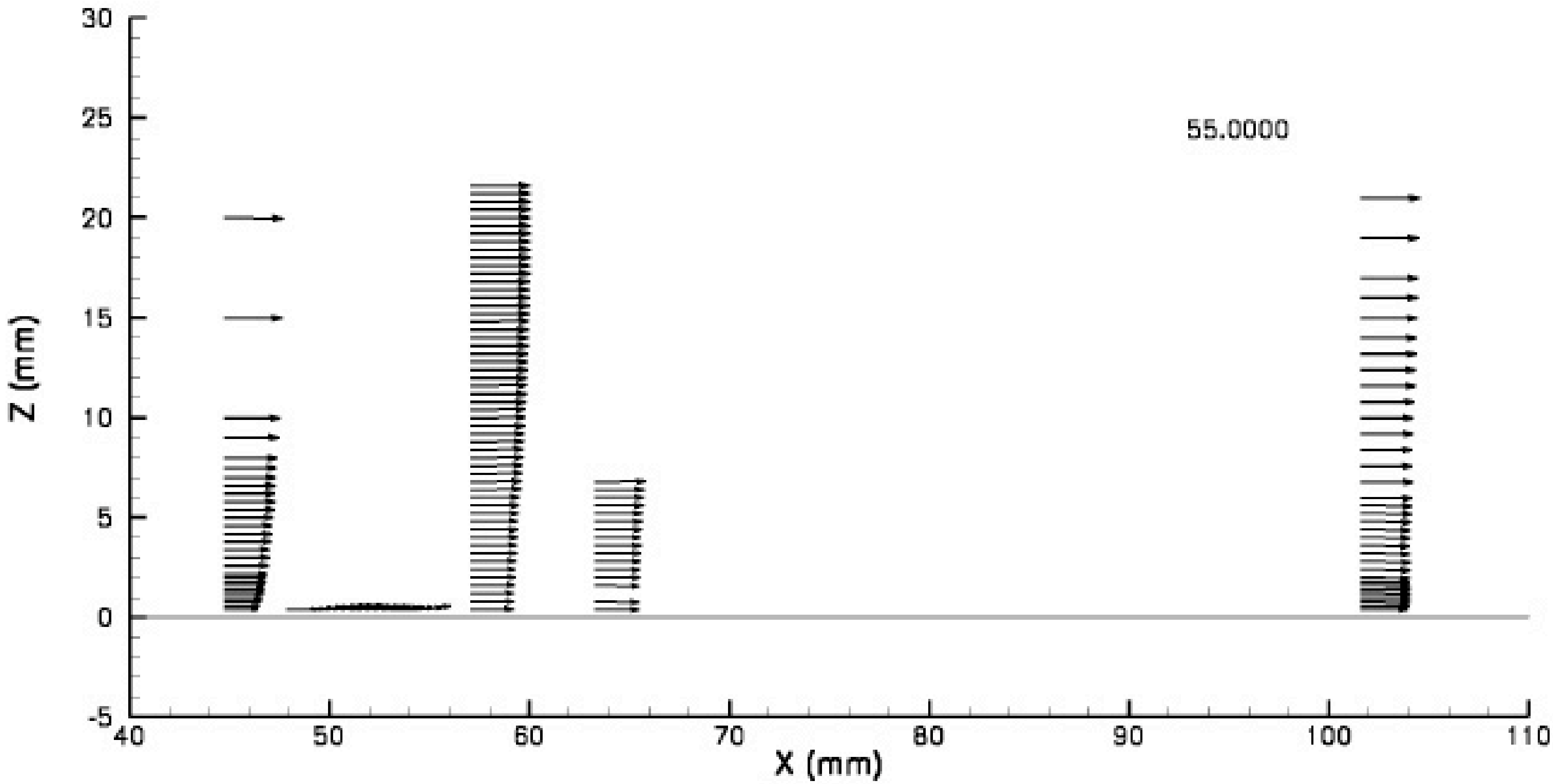
Phase-Averaged 3-D LDV Data



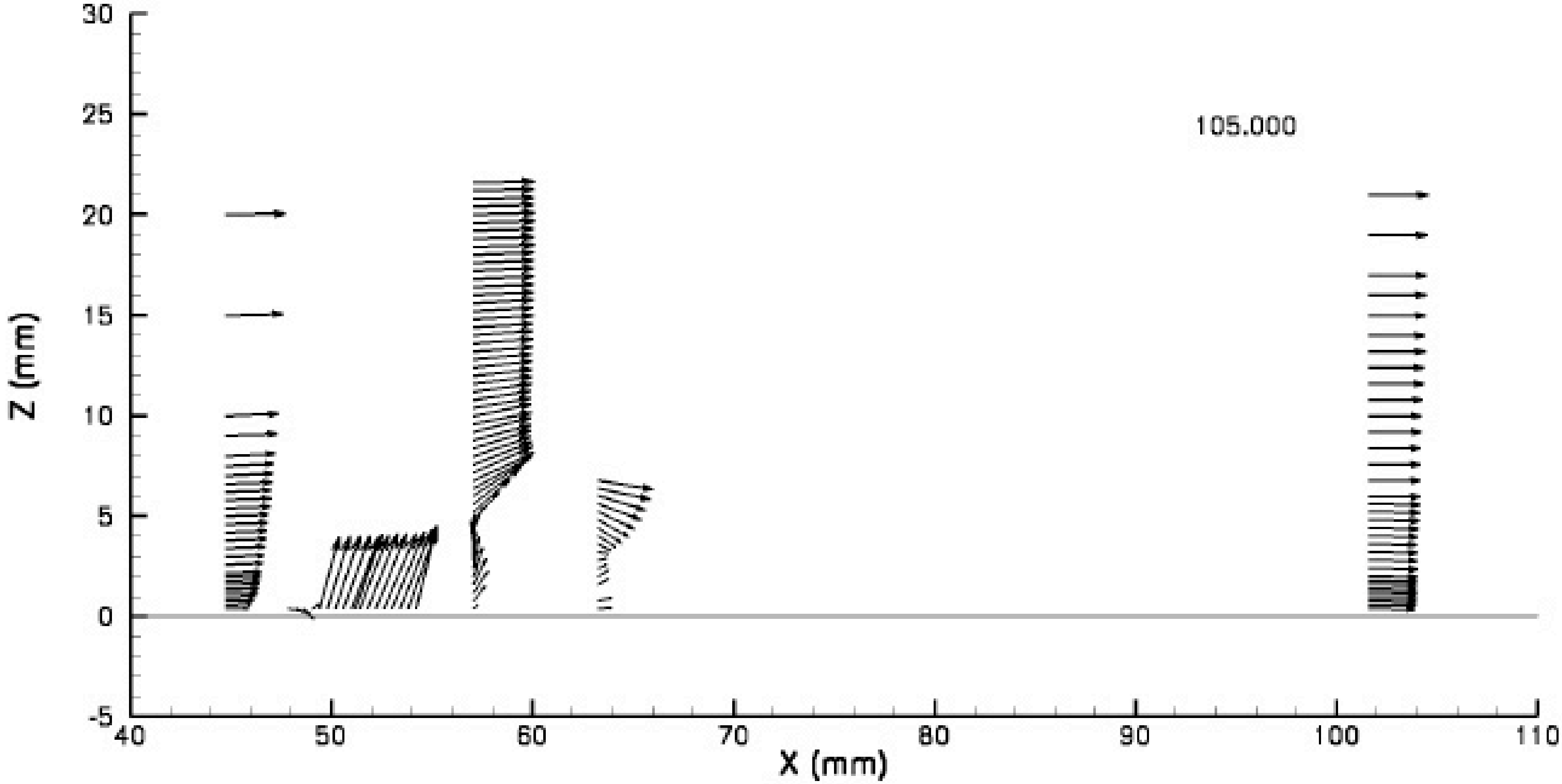
3-D LDV Data -- Suction -- ϕ = 315°



3-D LDV Data -- Transistion -- □ = 55°

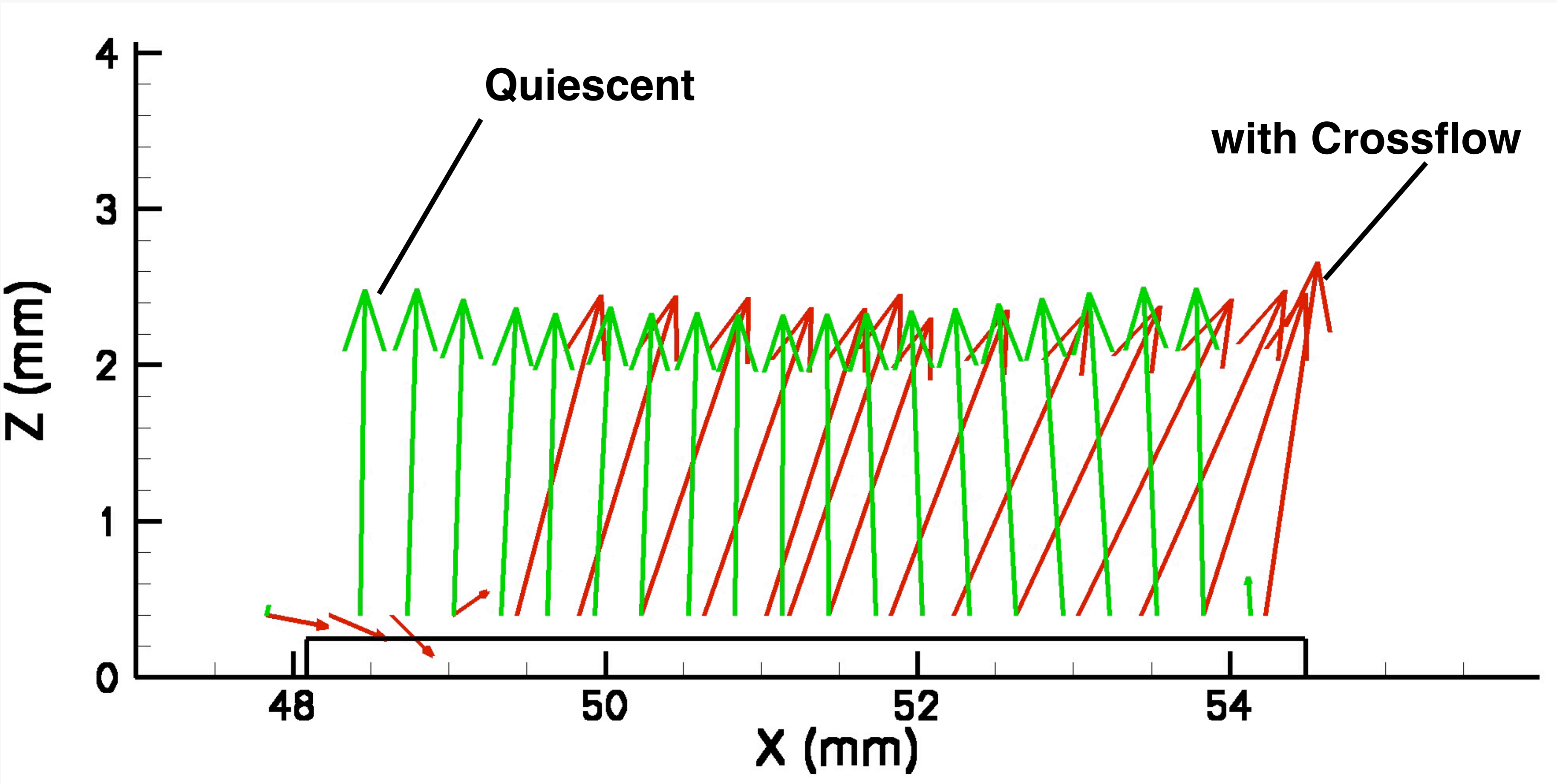


3-D LDV Data -- Exhaust -- [illegible] = 105°

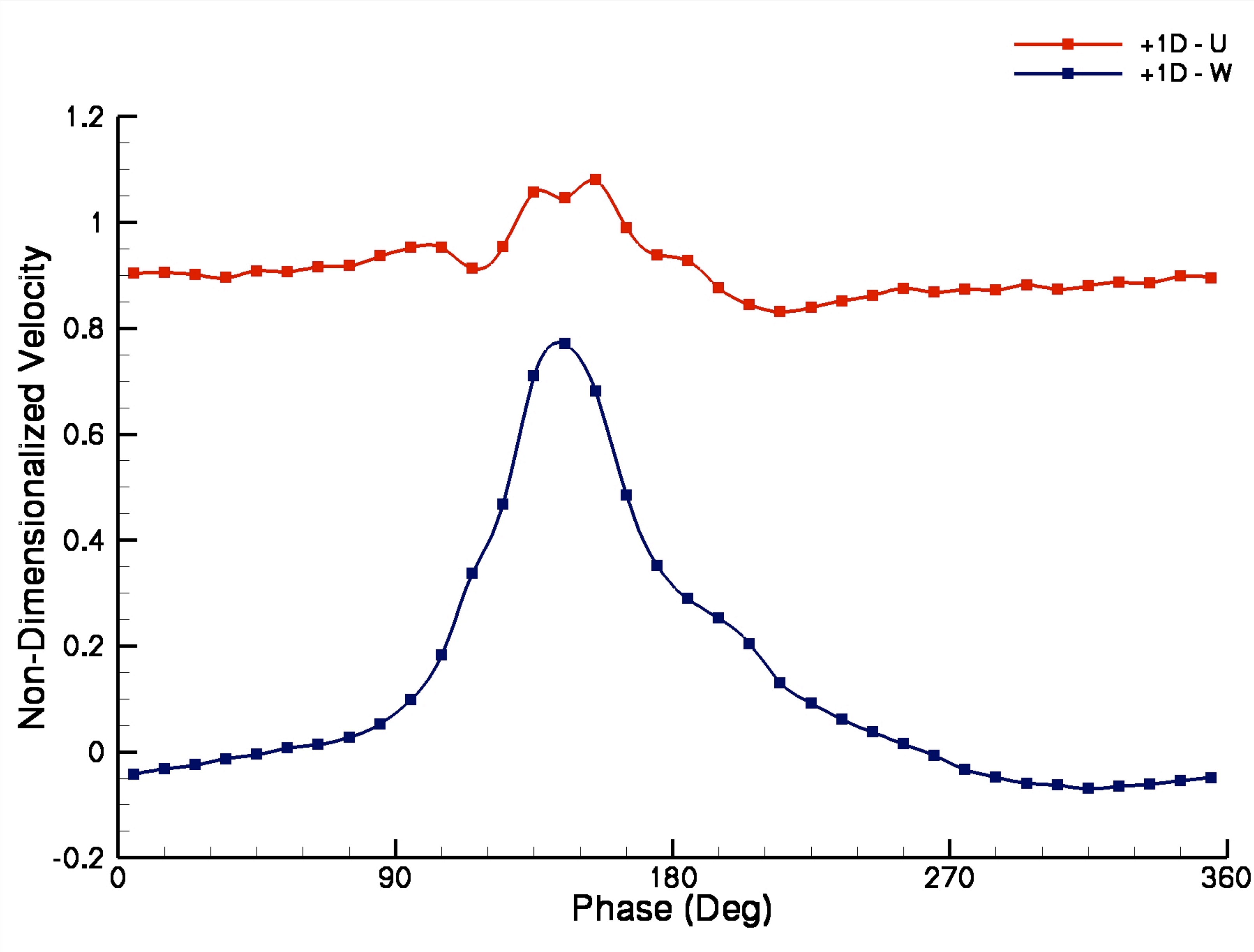


3-D LDV Data -- "Exit" Profile -- □ = 115°

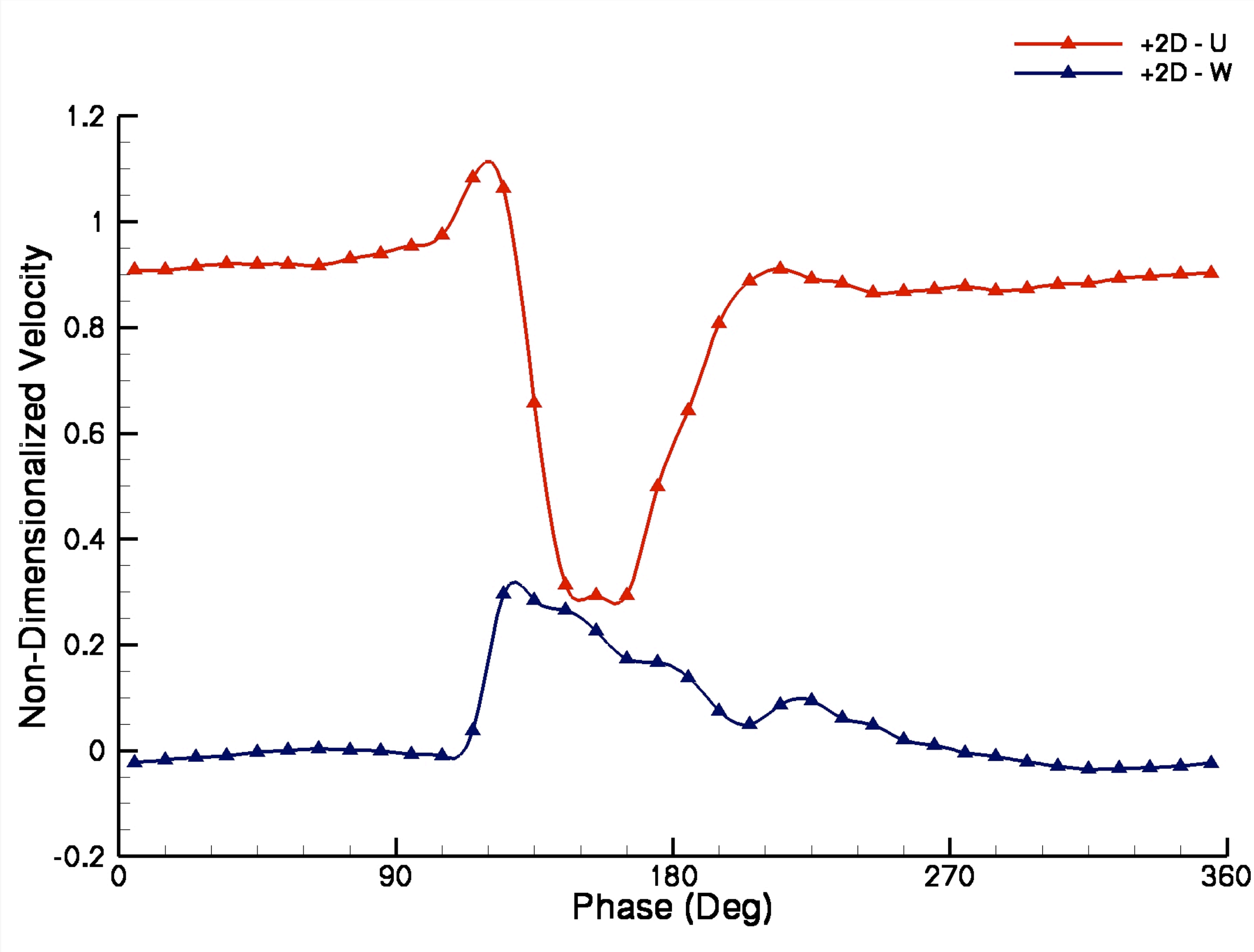
400 □m off surface



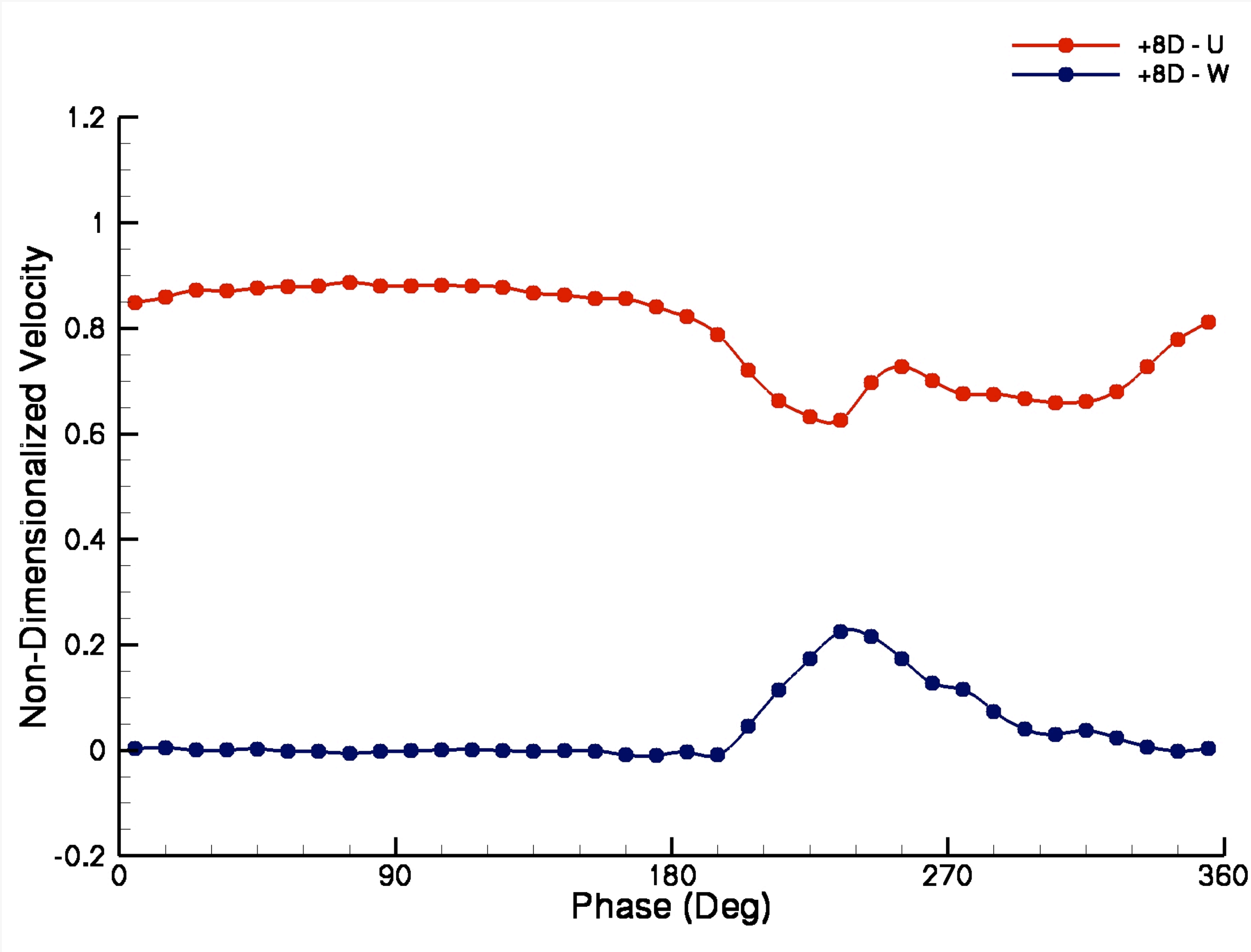
LDV Velocity Signature at (57.15, 0, 10.0)



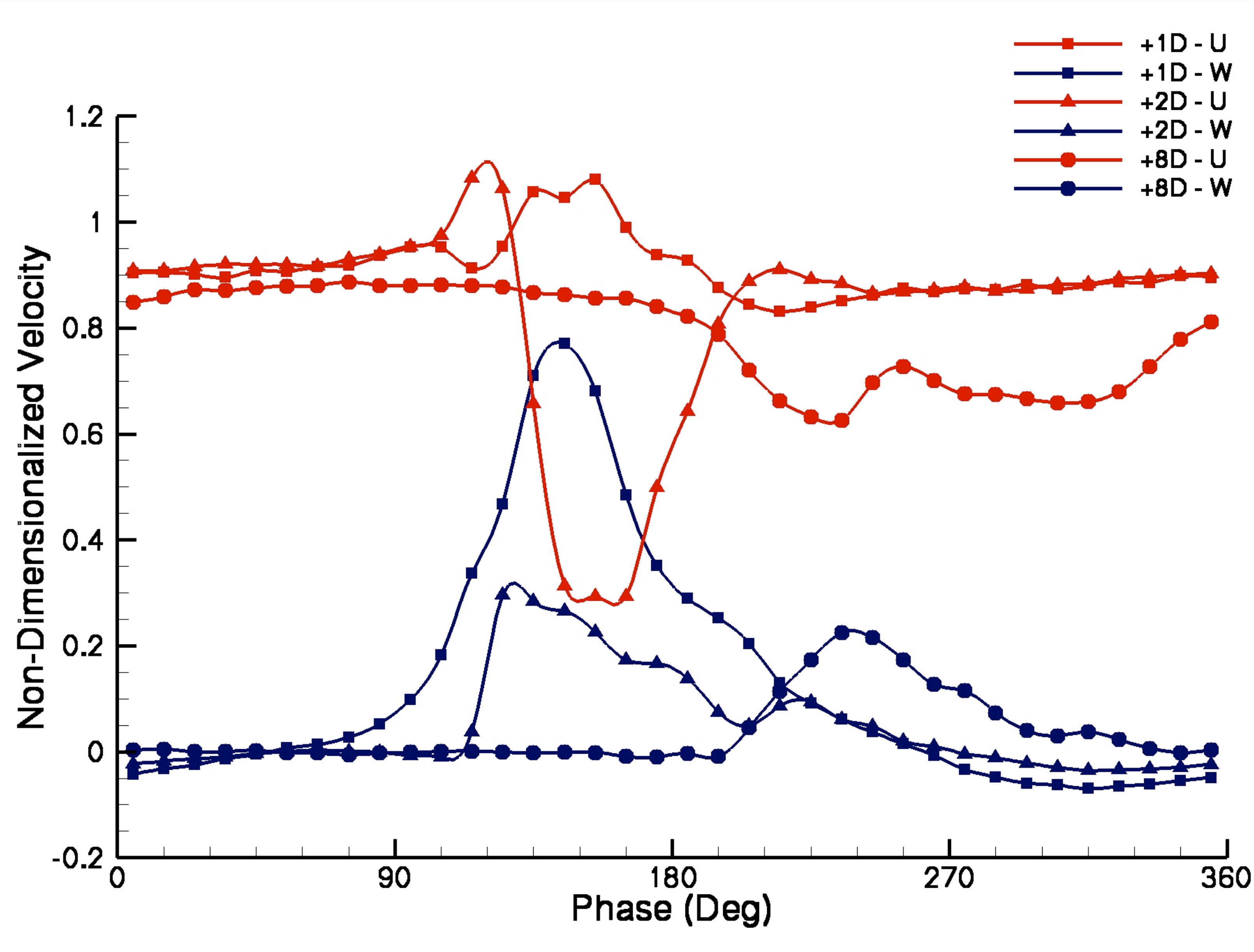
LDV Velocity Signature at (63.5, 0, 10.0)



LDV Velocity Signature at (101.6, 0, 10.0)

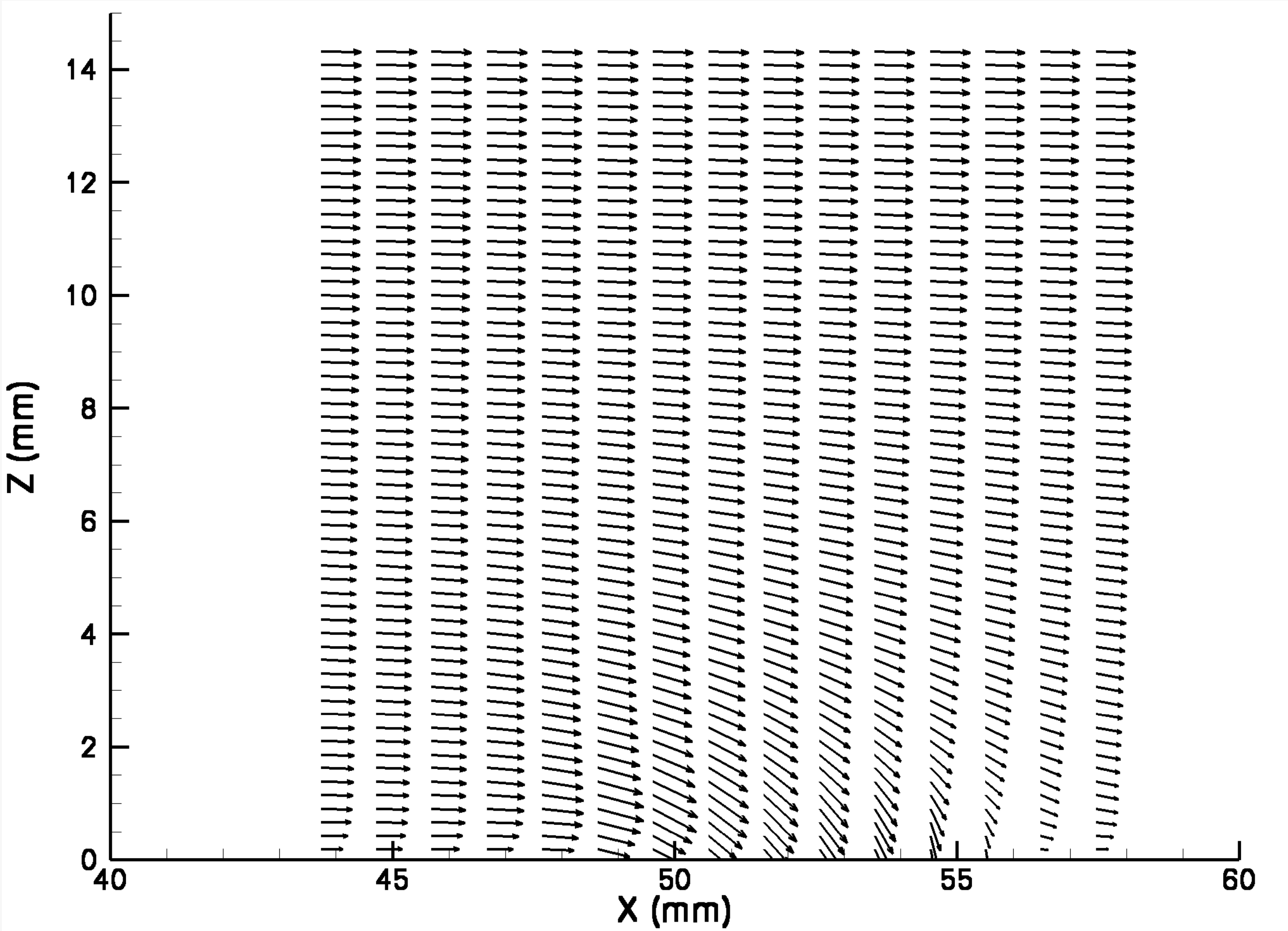


LDV Velocity Signatures, x = 1D, 2D, 8D, and z = 10.0

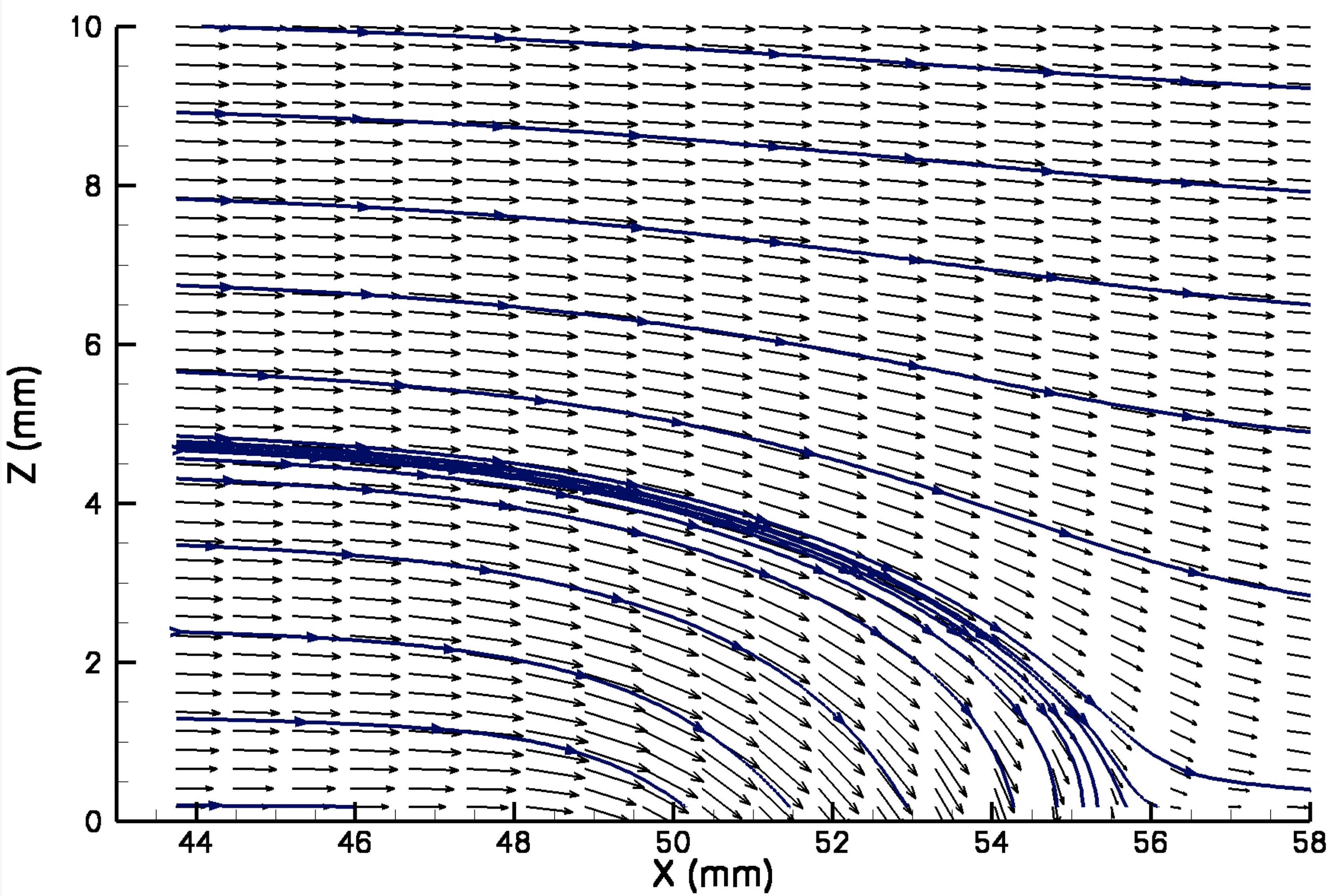


2D-PIV -- Centerline Plane (Streamwise Direction)

Velocity Vectors (Only every 4th column plotted)

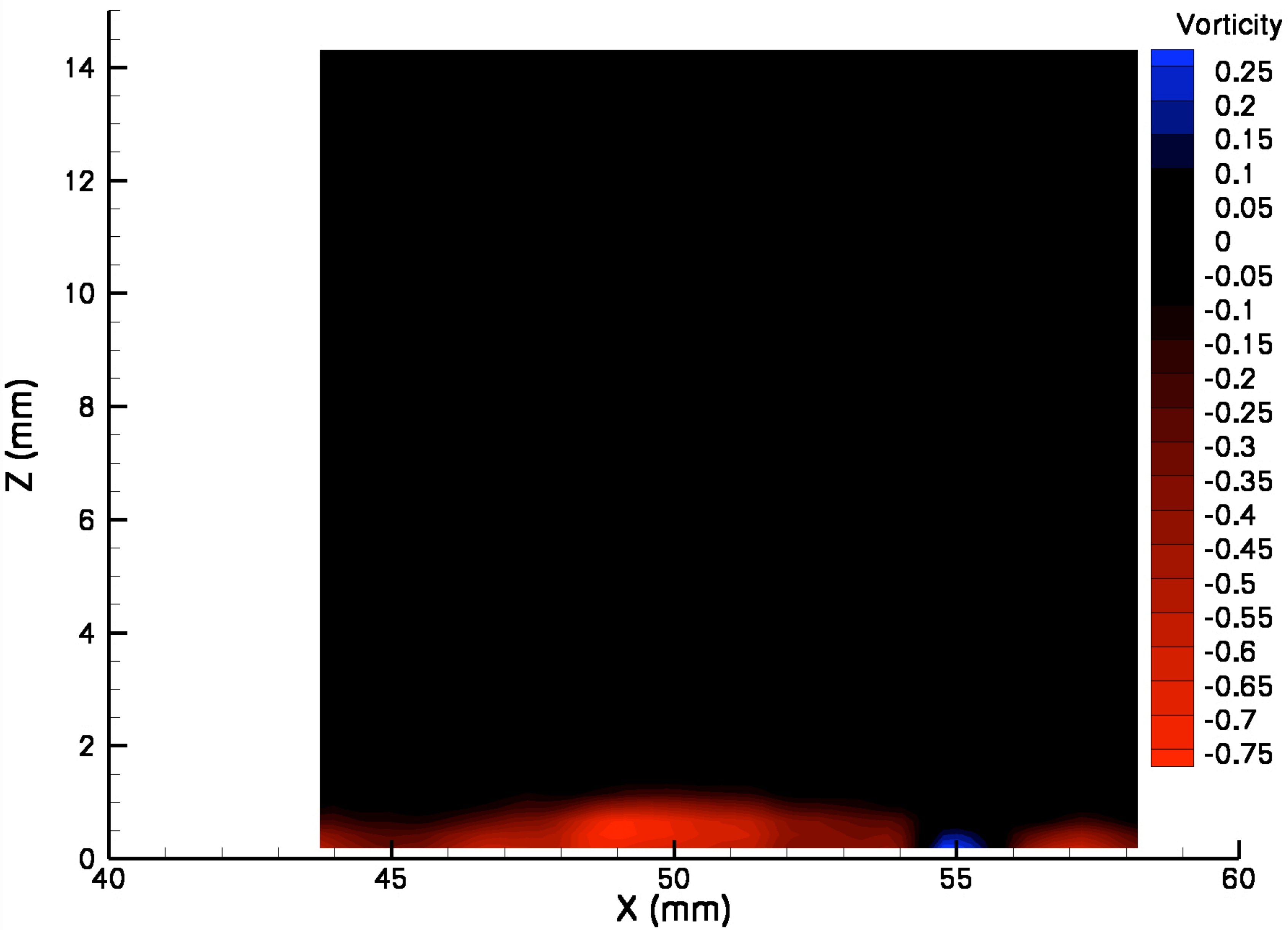


2D-PIV Results in the area of the jet exit at □=0°

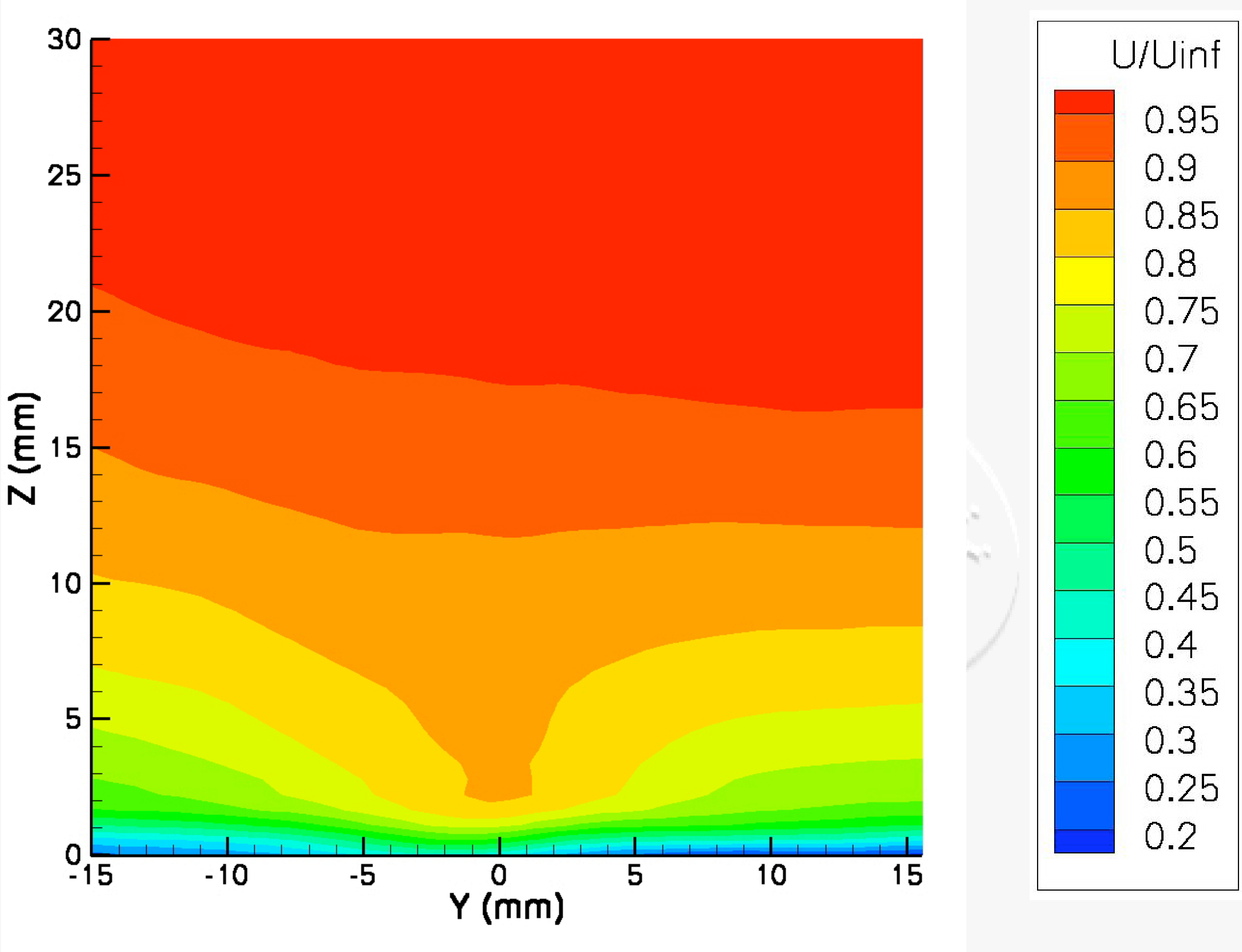


2D-PIV -- Centerline Plane (Streamwise Direction)

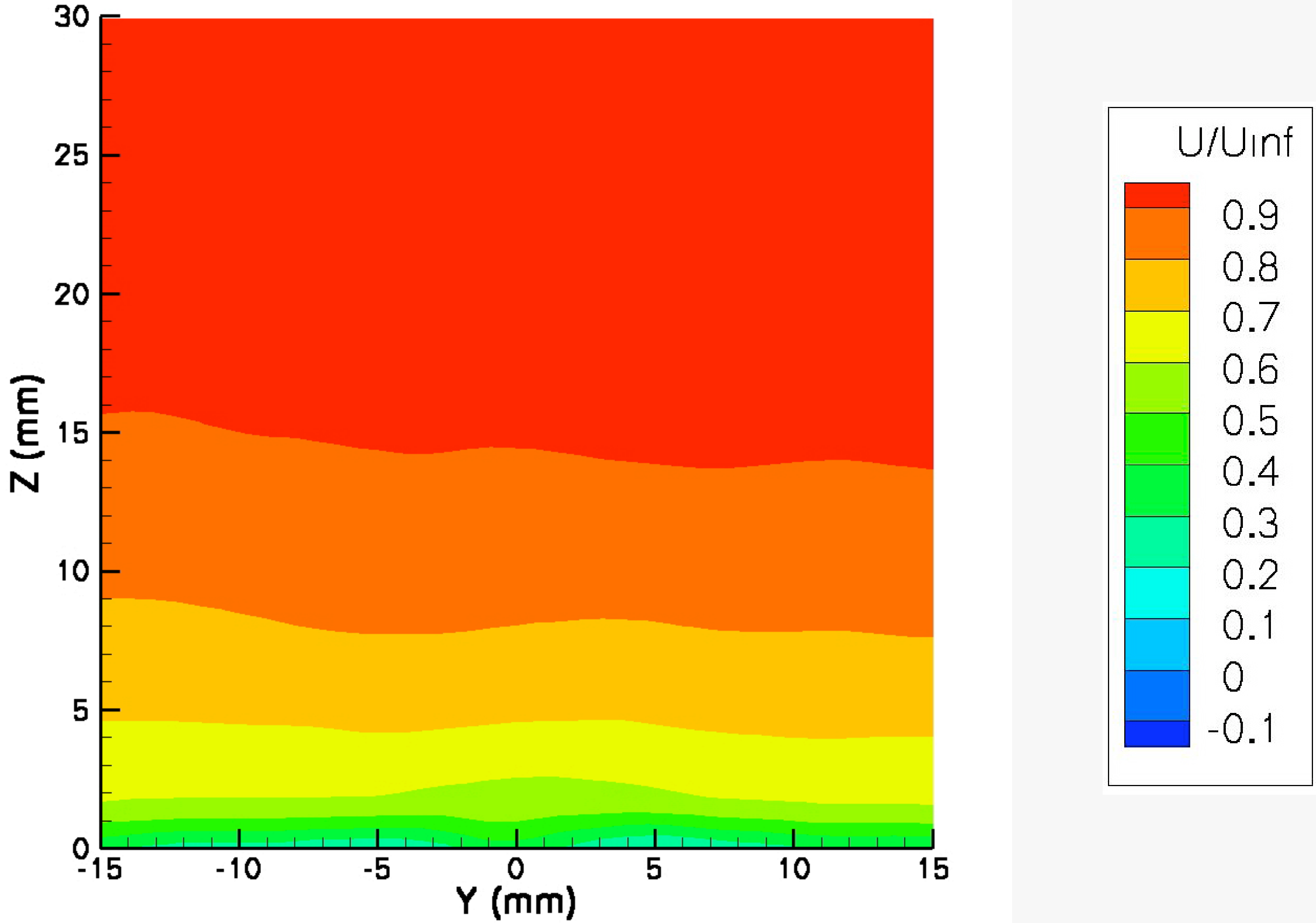
Vorticity Contours



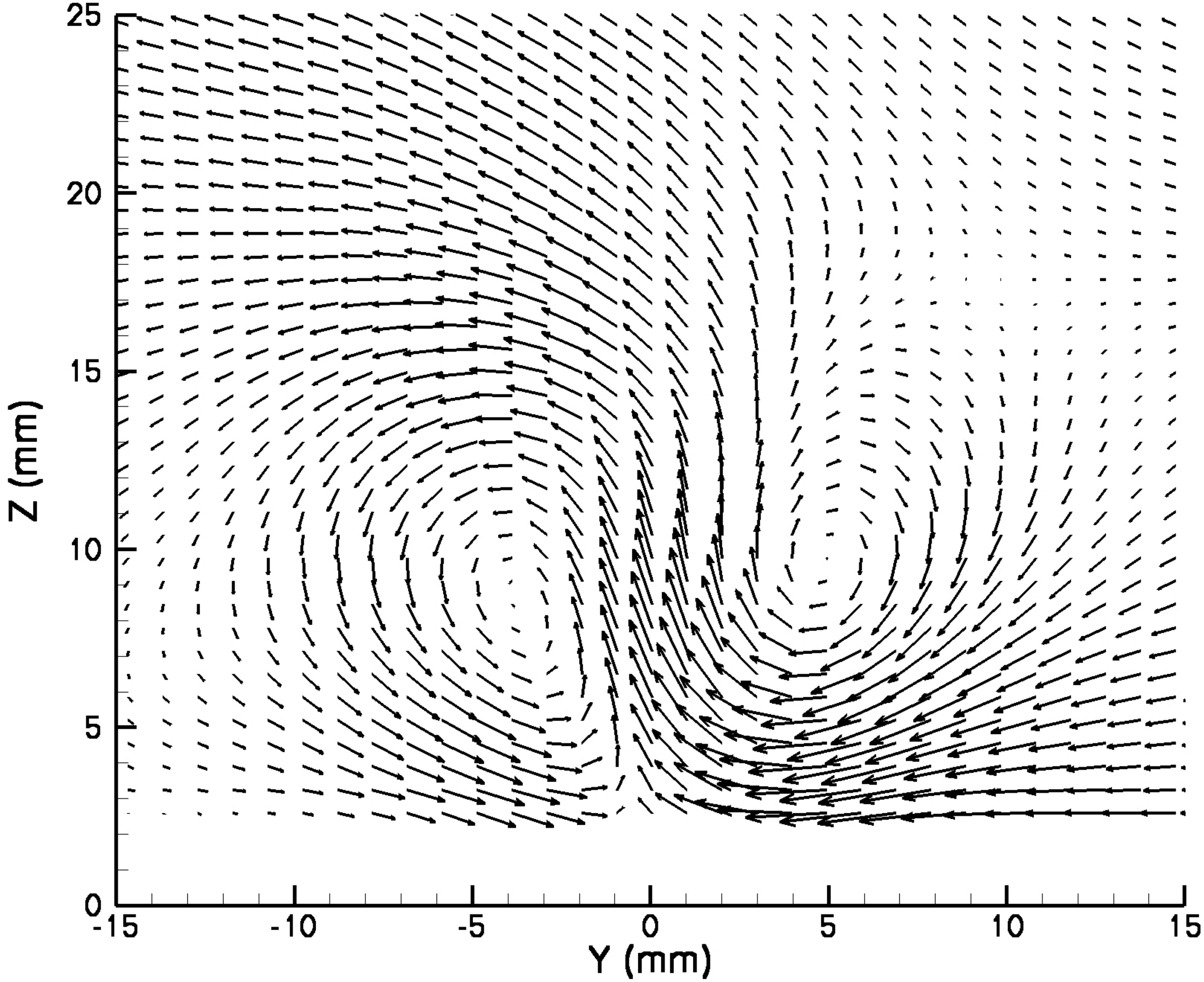
1-D Upstream of Jet Centerline -- SPANWISE



1-D Downstream of Jet Centerline -- SPANWISE



Mean Flow -- x = +4D



Summary

- The interaction of an isolated synthetic jet and a turbulent boundary layer was studied experimentally. The flowfield proved to be a challenging one to measure.

- To facilitate the use of the experiment as a CFD benchmark, the approach boundary layer, cavity pressure, diaphragm displacement, and velocity field were documented in a phase-averaged sense. Multiple measurement techniques were applied to the velocity field to assess the relative accuracy of each.

- Further analysis of the experimental data for Case 2 will be presented at the 2nd AIAA Flow Control Conference in June in Portland, Oregon.